Design document for Egg Pasteurization unit

For use in a mayonnaise production plant.

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Synopsis

The pipeline and equipment from the egg storage tank to the mayonnaise mixing tank was designed. Only the tanks and mixers were excluded from the design. The plant is designed to process 35 000 kg/h salted whole egg in Johannesburg, South Africa.

A plate and frame heat exchanger was selected due to it being more compact and more easily cleaned. The system has a regenerative section, a heating section and a cooling section. The Alva Laval Frontline 8 was selected as the heat exchanger.

The egg was kept at a steady temperature of 60 ˚C for five minutes inside an internal holding tank (IHT). The tube length inside the IHT is 406. 7 m.

In order to avoid whipping, and to ensure proper hygiene, a positive displacement (PD) twin screw type pump was selected for pumping the eggs. It will be installed with a variable speed motor and a pressure relief safety valve. Centrifugal pumps will be installed for the heating and cooling liquids.

All the pipes will be made from AISI 316 stainless steel due to hygienic reasons. All the product lines will have 3.5 inch nominal diameters.

A heating tank and a cooling tank will be used to supply water at a constant temperature to the heat exchangers. A heating coil will be used in the heating tank, and a cooling coil (containing a refrigerant) will be used in the cooling tank.

Butterfly valves will be used in the product lines, due to being Clean in Process (CIP). Ball valves will be used in the utility lines, since they are the cheapest.

Keywords: heat exchanger, internal holding tank, pump design, control valve design

Contents

Nomenclature

Symbol	Description	Units
$A_{required}$	Area required for heat transfer	m^2
A_1	Effective plate area	m^2
A_{1p}	Projected plate area	m^2
A_e	Total developed area	m^2
b	Mean channel width	mm
Cp	Heat capacity	J kg^{-1} K^{-1}
Ch	Constant	-
d	Diameter	mm
D	Diameter	m
D_h	Hydraulic diameter	m
D_p	Port diameter	m
D_c	Design factor	-
f	Constant	-
g	Gravitational acceleration	m s^{-2}
G_c	Channel mass velocity	kg s^{-1}
G_p	Port mass velocity	kg s^{-1}
h_{ext}	External convective heat transfer coefficient	W m^{-2} K^{-1}
h_{int}	Internal convective heat transfer coefficient	W m^{-2} K^{-1}
h_c	Convective heat transfer coefficient of cold fluid	W m^{-2} K^{-1}
h_h	convective heat transfer coefficient of hot fluid	W m^{-2} K^{-1}
k	Thermal conductivity	W m^{-1} K^{-1}
L	Length of pipe	m
$L_{required}$	Length of pipe required for heat transfer	m
L_v	Length of plate	m
L_w	Width of plate	m
Nu	Nusselt number	-
m	Mass flowrate	kg s^{-1}
N_{CP}	Number of channels per pass	-
N_t	Number of plates	-
N_p	Number of passes	-
n	Constant	-
Pr	Prandtl number	-
ΔP_a	Pressure difference due to fluid mover	kPa
ΔP_{cv}	Frictional pressure loss in control valves	kPa
ΔP_{EL}	Pressure difference due to elevation	kPa
ΔP_{EP}	End point pressure difference	kPa
ΔP_{EQ}	Frictional pressure loss in equipment	kPa

ΔP_f	Frictional pressure loss due to pipe sections and components	kPa
$\Delta P_f'$	Total frictional pressure loss	kPa
ΔP_c	Port pressure loss	kPa
ΔP_p	Channel pressure loss	kPa
Q_{added}	Heat added by heating coil	W
$Q_{convection}$	Heat lost through convection	W
$Q_{radiation}$	Heat lost through radiation	W
Q_R	Required heat transfer	W
Q_f	Actual heat transfer	W
$Q_{radiation}$	Heat lost through radiation	W
Ra_L	Rayleigh number	-
Re	Reynolds number	-
R_{fh}	Fouling factor – Hot side	K W^{-1}
Rf_c	Fouling factor – Cold side	K W^{-1}
T_e	Exit temperature	K
T_i	Inlet temperature	K
T_{inf}	Surrounding temperature	K
T_s	Surface temperature	K
T_{surr}	Surrounding temperature	K
ΔT_1	Temperature difference at entrance	K
ΔT_2	Temperature difference at exit	K
ΔT_{lm}	Log mean temperature difference	K
U	Total heat transfer coefficient	W m^{-2} K^{-1}
U_f	Overall heat transfer coefficient	W m^{-2} K^{-1}
W	Mass flowrate	kg hr^{-1}
Greek		
β	Volume expansion coefficient	K^{-1}
ϵ	Roughness factor	mm
ϵ_{rad}	Emissivity	-
μ	Dynamic viscosity	cP
μ_w	Dynamic viscosity at wall temperature	cP
ρ	Density	kg m^{-3}
σ	Boltzman constant	W m^{-2} K^{-4}
φ	Surface enlargement factor	-

1 Introduction

Pasteurization, a technique developed by Louis Pasteur in the nineteenth century, has become a very important aspect of food processing in modern engineering. It prevents the spread of various diseases, like tuberculosis, scarlet fever, and typhoid, by killing all of the pathogenic bacteria. The process involves the heating of the food or liquid to be pasteurized and then keeping the food or liquid at the elevated temperature for at least three minutes.

A mayonnaise manufacturing plant in Johannesburg, wants to a pasteurization plant to their process in order to pasteurize the egg that is used in the production of their mayonnaise.

This pasteurization of eggs is important for the purpose of killing bacteria, especially salmonella. The temperature to which the egg needs to be elevated is between 56 ºC to 61 ºC. The egg product then needs to stay at this temperature for at least 3 minutes. This design, however, assumes a minimum residence time of 5 minutes. Three plate heat exchangers, as well as one internal holding tank forms the basis of this pasteurization unit.

2 Process Selection

Figure 1 shows the Pipe Flow Diagram (PFD) for the whole process.

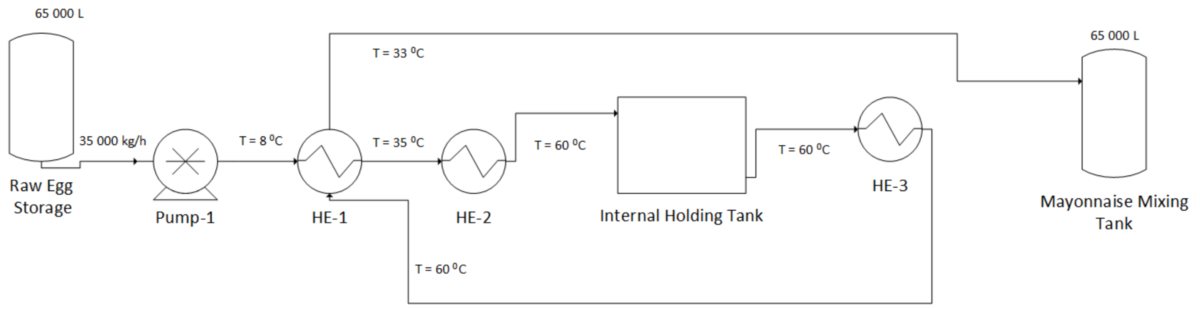

Figure 1: The PFD of the designed plant.

2.1 Heat exchangers

There are mainly two types of heat exchangers that can be used for liquid-liquid heat exchange. These are plate and frame heat exchangers (PHE's) and shell and tube heat exchangers (STE's).

PHE's are more compact than STE's, because they can achieve better heat transfer at an equivalent unit size. The PHE is easier to clean and maintain although capital costs are higher for PHE's.

Since a food product for human consumption is being produced, hygiene is one of the most important factors for the selection of the heat exchanger. Thus, a heat exchanger needs to be selected that is easy to clean and of which the inside can easily be accessed for scheduled checks.

Due to the above-mentioned reasons, a plate and frame heat exchanger consisting of three sections was selected.

The first section is the regenerative heat exchanger where heat is exchanged between the pasteurised and unpasteurised egg. This is to reduce the energy used to heat the unpasteurised egg up to 60 ˚C, and to cool the pasteurised egg down to 5 ˚C.

The second section is the heating heat exchanger, where the unpasteurised egg is heated to the correct temperature for pasteurisation. This is achieved by using hot water as the heating fluid.

The last section of the total unit is the cooling heat exchanger, where the pasteurised egg's temperature is reduced to avoid further growth of salmonella. This cooling is achieved using cold water.

There are three major companies globally that currently design plate and frame heat exchangers. To save on capital cost a standard frame from Alfa Laval was selected. The Frontline 8 was selected as it is specifically designed for the food and beverage industry, has superior cleaning ability and a flexible plate configuration.

Full specifications of the Alfa Laval Frontline 8 can be found at:

https://github.com/WillemASmit/CIO_Group_6_Design .

2.2 Internal holding tank

The internal holding tank's function is to keep the temperature of the heated egg at a steady temperature for about five minutes. The tank needs to be large enough to keep the heating fluid's (water) temperature at a steady value, but the outside surface area must be minimized in order to minimize the heat loss through the walls of the tank. It is absolutely necessary to have a device installed that will keep the liquid egg at an elevated temperature for the required amount of time. Since the heat lost through the pipes will be so great that the temperature drop throughout the pipe will be too much, this piece of equipment becomes essential.

2.3 Pump 1

Pumping eggs present engineers with several problems, such as shear sensitivity and hygiene issues. Shear sensitivity leads to the whipping problem found in centrifugal pumps (FRIP, 2010). To overcome both of these issues, a positive displacement (PD) type pump was chosen to transfer the raw eggs to the heat exchanger and ultimately to the Mixing Tank. A twin-screw pump was then selected as the PD pump of choice. This selection was made for a number of reasons. Positive displacement pumps achieve a higher discharge pressure for all flowrates, without losing substantial efficiency, whilst maintaining a better volumetric efficiency for viscous substances (Engineering_Toolbox, 2016). One main characteristic of positive displacement pumps is that they do not show a decrease in flow rate as the discharge pressure changes (Blevins, 2014a). A fixed amount of liquid is displaced for every rotation and the only way to alter the flow rate would be to change the number of rotations per second. Since control valves alter the flow rate through a pump indirectly by changing the pressure difference in the discharge line, a control valve will be ineffective. This can be overcome by using a throttling valve with a backpressure regulator (Blevins, 2014b), but this method is outside of the scope of this design. The twin screw type pump is capable of pumping liquids at flow rates ranging from 189 – 56 781 lpm with delivery pressures ranging from 3 - 310 bar (PumpScout, 2014; ENCE) which is well beyond the unit's requirements. Twin screw pumps have the added advantage of having little to no pulsations, which makes them suitable for heat exchanger supply (Fristam, 2016a). Twin screw pumps are often also designed to be fully CIP'able and are thus considered hygienic and suitable for food processing (Ampco, 2015). The pump installed will therefore be equipped with a variable speed drive and a pressure relief safety valve.

2.4 Centrifugal pumps

The fluid movers for the heating and cooling liquids have less limitations and a centrifugal pump will be sufficient. These pumps can be effectively controlled by a control valve; thus, a control valve will be used in the discharge line. Centrifugal pumps are "the best choice for low viscosity liquids and high flow rates" (PumpScout, 2014), and are low cost for both installation and maintenance (ENCE). They are effective at flow rates ranging from 10 – 16 000 lpm and discharge pressures of 10 - 1000 m head. (PumpScout, 2014; ENCE) which is well within our operating range.

2.5 Piping materials and fitting

All the pipes carrying egg will be of the same size, since the flow rate through the pipes is the same. Furthermore, all of the pipes will be made from AISI 316 stainless steel, due to the hygiene requirements for food production.

2.6 Cooling and heating tanks

The two tanks are necessary to supply water at a constant temperature to the two heat exchangers. Inserting two tanks in series in one line was considered, but due to the complexity this was decided against. The most important factor to consider regarding these tanks is that their size will determine the average residence time of the water, and will therefore influence the completeness of heat transfer to the water.

It was decided that an electric coil should be used in the heating tank and a vapour compression cycle, using a known refrigerant gas, in the cooling tank.

2.7 Valves

2.7.1 Butterfly valves in product line

This is standard for use in the food industry, since the valves are sanitary and do not become dirty very often. This is because the entire valve is in contact with cleaning fluid during CIP. All parts of the valve, those in contact with the fluid when open as well as those in contact with the fluid when closed, will thus be cleaned during CIP.

2.7.2 Ball valves in heating and cooling lines

These valves are the cheapest valves on the market, and since the heating and cooling water does not have to be completely sanitized, it was decided that this valve would be ideal.

2.7.3 Pressure relieve valve

This valve was added as a safety precaution, especially since there is a PD pump. This pump could cause the pressure to rise enormously if it has an obstruction blocking the flow in its delivery line. The valve will then release and let the fluid be pumped back into the tank, relieving the pressure and saving the system from a possible blow out.

3 Equipment

The full piping and instrumentation diagram (P&ID) for the process and all of its equipment can be seen in Figure 2 below. For higher resolution pictures of the process visit https://github.com/WillemASmit/CIO_Group_6_Design .

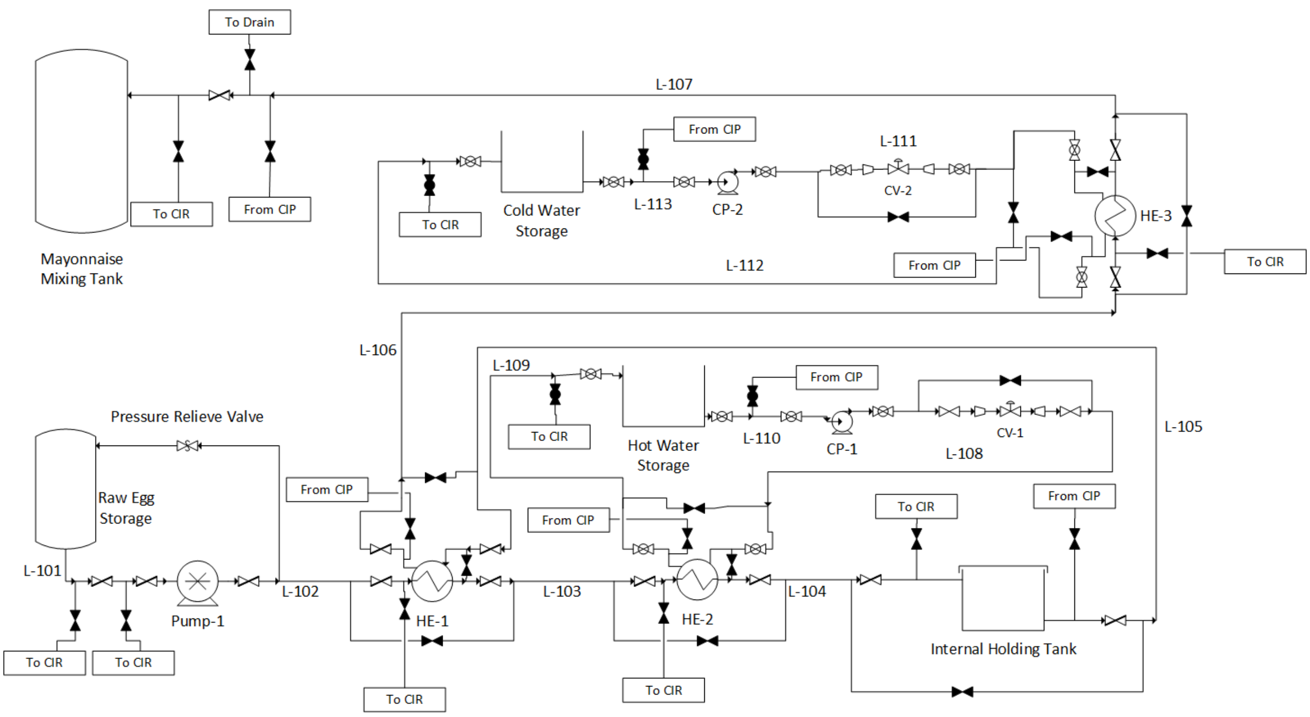

Figure 2: A P&ID of the plant

3.1 Heat exchangers

Figure 3 displays the P&ID over the heat exchanger section.

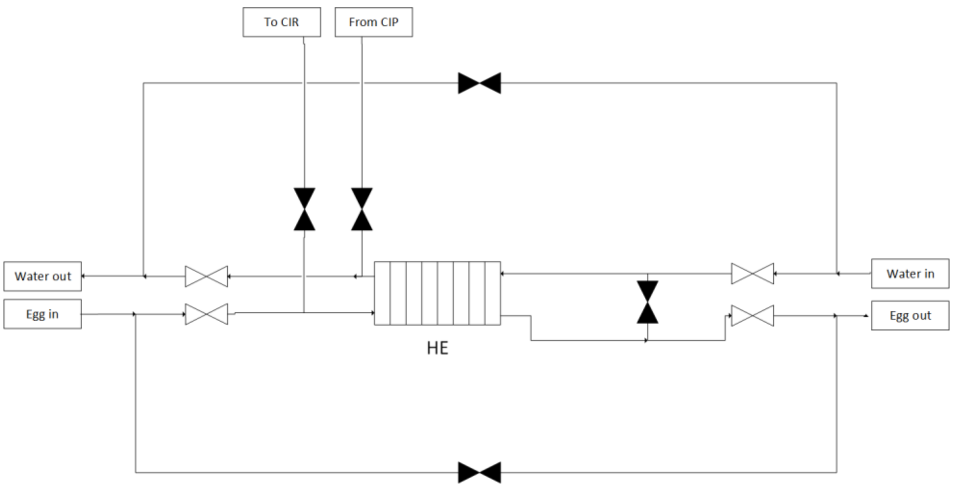

Figure 3: The P&ID for the heat exchangers.

All the possible configurations for an Alfa Laval Frontline 8 heat exchanger can be found at https://github.com/WillemASmit/CIO_Group_6_Design. All three heat exchangers use the Clip 8-G plates manufactured from AISI 316 stainless steel with EPDM gaskets, since they are more resistant to chemicals used to CIP the heat exchangers. The heat transfer plates are designed with a chevron angle of 30˚ for all heat exchangers. The methodology for each heat exchanger is found in Heat exchangers.

3.1.1 Heat exchanger 1

The Regenerative PHE's specifications are shown in **Table 1** below.

Table 1: Design Specifications of Regenerative PHE

Parameter	Pasteurised egg (Hot fluid)	Unpasteurised egg (Cold fluid)
Temperature inlet (˚C)	60	8
Temperature outlet (˚C)	33	35
Design Flow rate (kg/h)	35 000	35 000
Number of Plates	112	
Number of Passes	2	
Pressure drop (kPa)	68.06	72.77
Actual Flow Rate (kg/h)	35000	35000
Convective heat transfer coefficient	3027	2558

(W/m^{2}K)	
Overall Heat Transfer Coefficient (W/m^{2}K)	627

3.1.2 Heat exchanger 2

The design specifications for the Heating PHE are show in **Table 2** below.

Table 2: Design Specifications of Heating PHE

Parameter	Water (Hot fluid)	Pasteurised egg (Cold fluid)
Temperature inlet (˚C)	80	35
Temperature outlet (˚C)	60	63
Design Flow rate (kg/h)	30 000	35 000
Number of Plates	128	
Number of Passes	2	
Pressure drop (kPa)	26.67	52.90
Actual Flow Rate (kg/h)	31397	35 000
Convective heat transfer coefficient (W/m^{2}K)	7478	2862
Overall Heat Transfer Coefficient (W/m^{2}K)	735	

3.1.3 Heat exchanger 3

The design specifications of the Cooling PHE are given in **Table 3** below.

Table 3: Design Specifications of Cooling PHE

Parameter	Pasteurised egg (Hot fluid)	Water (Cold fluid)
Temperature inlet (˚C)	33	1
Temperature outlet (˚C)	5	20
Design Flow rate (kg/h)	35 000	34 000
Number of Plates	448	
Number of Passes	4	
Pressure drop	55.40	33.44

(kPa)		
Actual Flow Rate (kg/h)	35 000	33 041
Convective heat transfer coefficient (W/m^{2}K)	1556	3954
Overall Heat Transfer Coefficient (W/m^{2}K)	564	

3.2 Internal holding tank

The design specifications of the IHT are shown in **Table 4** below.

Table 4: Design of the Internal Holding Tank.

Parameter or Specification	Value or Description
Material (wall)	Brick
Height	2 m
Diameter	1.2 m
Total fluid volume	5809 L
Total heat loss	4.433 kW
Method of heating	Electric Coil
Internal piping length	410 m
Internal piping material	AISI 316
Internal piping layout	Multiple helix
Total pressure drop (@ W_n)	108 kPa
Tank fluid temperature	61 ºC
Piping fluid temperature	59.9 ºC
Cover/Lid material	High Density Polyethylene
Max. pressure on wall	11.7 kPa
Endings	Flanged

The piping within this tank will consist of multiple helixes that are located within one another. This is to minimize its pressure drop, since there will be no elbows in this part of the pipeline. The manufacturing cost will be significant, but since the equipment is not subject to high levels of erosion, the equipment should last a long time if it is maintained properly.

Another advantage of the helix system is that the forces generated by the change in momentum of the fluid will cancel each other out, and will therefore not place the pipes under a significant amount of strain.

3.3 Twin screw pump

The design specifications for the Twin screw type pump are given in **Table 5** below.

Table 5: Specifications for Twin screw type pump used for product displacement

Fluid	Whole raw salted eggs	
Temperature	Ambient (25ºC)	
Viscosity	0.012 Pa.s	
Density	1127 kg/m^3	
	Normal flow	Design flow
Flow rate [kg/s]	9.72	11.18
Flow rate [m^3/h]	31.05	35.71
ΔP_a [kPa]	428.41	559.96

The Eggs are assumed that the vapour pressure of the eggs at the given temperature is low enough for cavitation to not be an issue. Furthermore, Twin screw type pumps are capable of pumping liquid-vapour mixtures and should cavitation occur it will not result in significant damages to the pump mechanism. Therefore the NPSH is omitted from the specification.

The Fristam FDS 3 Twin screw pump is selected and can deliver flow of up to ≈75m^3/h at 5 bar pressure or 50m^3/h at ≈22bar. Its characteristic curve (Fristam, 2016b) is included in the appendix.

3.4 Centrifugal pumps

There are two centrifugal pumps in the system. The first brings hot water to the heating PHE and the second brings cold water to the cooling PHE.

Table 6 and Table 7 contain the specifications for the heating and cooling water pumps respectively.

Table 6: Specifications for heating water centrifugal pump

Fluid	Water	
Temperature [ºC]	60	
Viscosity [Pa.s]	0.00089	
Density [kg/m^3]	1000	
	Normal flow	Design flow
Flow rate [kg/s]	8.33	9.58
Flow rate [m^3/h]	30	34.5
ΔP_a [kPa]	66.91	66.93

$NPSH_a$	8.31	8.24

Table 7: Specifications for cooling water centrifugal pump

Fluid	Water	
Temperature [ºC]	1	
Viscosity [Pa.s]	0.00089	
Density [kg/m^3]	1000	
	Normal flow	Design flow
Flow rate [kg/s]	9.44	10.86
Flow rate [m^3/h]	34	39
ΔP_a [kPa]	82.42	82.21
$NPSH_a$ [m liquid]	13.00	12.91

Take note that these calculations rely on the control valves where the assumption was made (as discussed in the appendix) that $P_{a,d} = P_{a,n}$. Thus, these values are not completely accurate. Since the pumps are extremely similar two identical pumps will be installed.

The pump selected is the Calpeda BNMM 17/GE 230/50 HZ. It is a closed coupled single impeller centrifugal pump. The pump's approximate characteristics are summarised in Table 8 and full pump curves are available in the appendix (Calpeda, 2016).

Table 8: Pump Characteristics when operating at a flow rate of 40 m3/h

ΔP_a [bar]	0.98	Efficiency	75%
Power [kW]	1.47	$NPSH_R$ [m liquid]	2

3.5 Piping system

3.5.1 Product lines

Figure 4 displays the P&ID of the product lines.

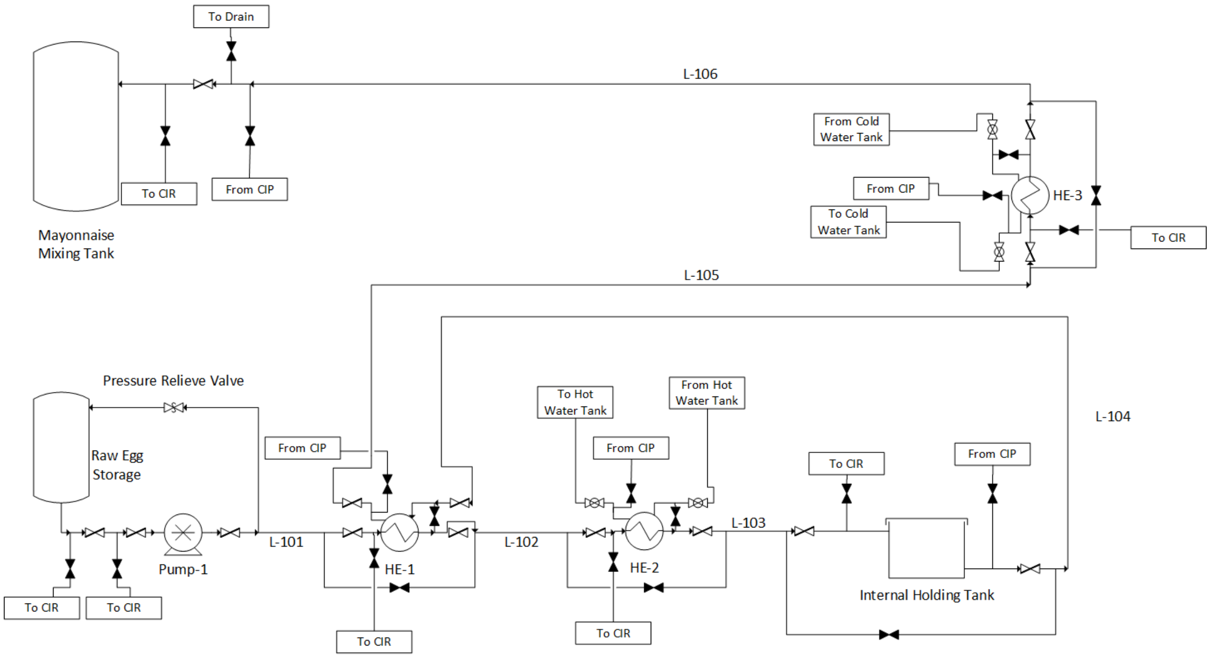

Figure 4: The P&ID of all the product lines.

The design specifications of the product lines are shown in **Table 9** below.

Table 9: Design of the product lines.

Parameter or Specification	Value or Description
Material	AISI 316
Diameter	3.5 " nom
Thickness/Schedule	S10
Endings	Flanged

3.5.2 Heating line

The design specifications of the heating line are shown in **Table 10** below.

Table 10: Design of the heating line.

Parameter or Specification	Value or Description
Material	AISI 316
Diameter	4 " nom
Thickness/Schedule	S5
Endings	Flanged

3.5.3 Cooling line

The design specifications of the cooling line are shown in **Table 11** below.

Table 11: Design of the cooling line.

Parameter or Specification	Value or Description
Material	AISI 316
Diameter	4 " nom
Thickness	S5
Endings	Flanged

In all of the above pipes a standard of four elbows (see Table 12) was placed between each piece of equipment, since it is possible to produce any exit in a three-dimensional cube by manipulating the entrance with four elbows.

3.5.4 Piping dimensions

Table 12: Piping dimensions for all labelled lines.

Pipe number	Length (m)	Number of Elbows	Number of soft Tees	Number of Butterfly valves	Number of Ball Valves
L-101	2	4	2	2	0
L-102	5	4	3	2	0
L-103	1	4	4	2	0
L-104	1.5	4	4	2	0
L-105	4.6	4	4	2	0
L-106	4.6	4	2	2	0
L-107	15.5	4	5	1	0
L-108	10	4	5	0	4
L-109	4	4	3	0	2
L-110	2	4	1	0	2
L-111	10	4	4	0	4
L-112	4	4	3	0	2
L-113	2	4	1	0	2

3.6 Hot and cold water storage tanks

Table 13: Design specifications for storage tanks.

Parameter	Hot water tank	Cold water tank
Diameter	3 m	3 m
Height	5 m	5 m
Method of heating/cooling	Electric coil	Vapour compression cycle
Volume	35 000 L	35 000 L

3.7 Control valves

Control valves are made to the specifications in Table 14 and Table 15 for the heating and cooling side respectively.

After iterating, we find that neither a 3” nor a 4” control valve size supports all 4 rules for an economic control valve size as described in the appendix of this document. In this case 3” and 4” control valves give ΔP control valve nominal that lie on the opposite sides of the acceptable range according to rule 2(d). Since a 4’’ control valve does not require the use of a reducer and enlarger and thus reduces both cost in construction and total system pressure loss a 4” diameter control valve will be selected.

Table 14: Heating side control valve.

Diameter	4”	
C_{cv} Value	124	
Trim Type	Equal % trim	
Nominal	Design	Nominal
F(x)	1	0.60

Table 15: Cooling side control valve.

Diameter	4”	
C_{cv} Value	124	
Trim Type	Equal % trim	
	Design	Nominal
F(x)	1	0.60

3.8 Pressure relief valve

The pressure relief valve will be selected to the following specifications.

Table 16: PSV Specifications.

Diameter	4” Nominal
Release Pressure (kPa)	781

The selected release pressure was chosen to be 10% above the delivery pressure at design conditions.

4 Wastes

Any egg product that is produced prior to steady state being reached would have to be discarded. This is due to the egg not being properly pasteurized or that there are still significant amounts of water mixed with the egg to be pasteurized, Section 5.1.1. If the egg stream was simply recycled through the heat exchanger until it reaches the desired temperature, it would spend too much time in the temperature range where the growth of the bacteria is promoted. Thus, to prevent this, the heating fluid must be circulated to preheat the pipes before the egg mixture is pumped through. Steady state should then be achieved soon enough to avoid any wastage.

4.1 Quantities

The only time that egg will go to waste will be during maintenance and hot commissioning periods. The amount of egg going to waste will be limited.

4.2 Properties

Please refer to https://github.com/WillemASmit/CIO_Group_6_Design for the properties and material safety and data sheets (MSDS) for all of the wastes.

5 Operating Procedures

5.1 Commissioning

5.1.1 Cold Commissioning

Confirm that valves can open and close and are in a good condition. These tests will be under non-operational conditions with empty pipes.

5.1.2 Hot Commissioning

Here the process is started up with real fluids. Firstly, open all of the valves, then turn on the pumps and start pumping all of the lines full of water. Note that the heat exchanging line should also be operation and up to temperature at this point. Now the water supply can be cut and the product can start getting pumped. All of the material will go to waste until the pumps have reached their set points and all of the water is already down the drain. The processed egg will then finally be pumped into the mayonnaise mixing tank.

5.2 Operating

In the operating stage, the various parameters will be monitored, to ensure that everything is stable. CIP will be done daily, which will include a Pre-rinse with water, Caustic Flush and a Post Rinse. Before any start-up of the plant, and after a CIP, there will be a sanitising step, where a chlorine solution will be used.

5.3 Shut Down

When Maintenance needs to be done, the plant will be shutdown, the whole system flushed with water, and a CIP will follow. The relevant valves will be closed and maintenance will commence. After maintenance is completed, the unit will once again be rinsed and a full CIP will be completed. The product line will also have to be sanitised before any product may be produced.

6 Safety

The main dangers associated with the system are pressure build-ups (especially after the positive displacement pump), and blowout of the pipes or other piping equipment. Leakages of CIP chemical, as well as hot water pipelines, also pose a threat. General plant safety measures apply for this plant, e.g. slipping hazards, falling objects, etc.

Concerning the hygiene of the plant, all personnel should wear hairnets, closed shoes and gloves at all times when on the premises.

Please refer to https://github.com/WillemASmit/CIO_Group_6_Design for all MSDS sheets of the various chemicals used in the process.

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Appendix

In this document, all of the equations used are given in the order they were used to calculate various parameters. Python as well as Jupiter Notebooks were used to solve all of the equations in iterative format, to increase the speed of designing the plant. Please visit https://github.com/WillemASmit/CIO_Group_6_Design to view of the code that was written to solve the equations stated below.

Heat exchangers

The design of all 3 heat exchangers followed the same methodology for the design. The methodology used is described step wise below.

The first step in the design is to specify the inlet and outlet temperature of all streams as well as the flow rate of the hot and cold fluid. Specify the plate design as an initial guess and number of plates and passes.

The first calculation that follows is hydraulic diameter (D_H) and surface enlargement factor (φ) using equation (1) and (2) respectively.

$$D_H = \frac{2b}{\varphi} \tag{1}$$

$$\varphi = \frac{A_1}{A_{1P}} \tag{2}$$

Where b is the mean channel spacing and A_1 and A_{1P} is the effective area and projected plate area.

After the above calculations are completed, the Nusselt number and thus the heat transfer coefficient for the specific fluid can be calculated with the correlation from Kumar.

$$Nu = C_h \left(\frac{D_h G_c}{\mu}\right)^n \left(\frac{C_P \mu}{k}\right)^{\frac{1}{3}} \left(\frac{\mu}{\mu_w}\right)^{0.17} \tag{3}$$

Where D_h is the hydraulic diameter, G_c is the channel mass velocity. μ, μ_w, k, C_p is properties of the fluid. C_h and n is dependent on the flow characteristics and chevron angle which is specified as initial guesses. To determine Ch and n, it is needed to determine the Reynolds number and channel mass velocity with Equation (4) and (5).

$$G_c = \frac{m}{N_{cp} * b * L_w} \tag{4}$$

$$Re = \frac{G_c D_h}{\mu} \tag{5}$$

Where m is mass flow rate, N_{cp} is number of channels and is calculated with Equation (6) and L_w is width of a plate.

$$N_{cp} = \frac{N_t - 1}{2N_p} \tag{6}$$

N_t is number of plates and Np is number of passes as specified in the beginning.

After all these calculations the pressure drop and heat transfer calculations can be completed and design can be checked and optimised for operating conditions.

The pressure drop calculations are as follows:

For the frictional channel pressure drop

$$\Delta P_c = 4f \left(\frac{L_v N_p}{D_h}\right)\left(\frac{G_c^2}{2\rho}\right)\left(\frac{\mu}{\mu_w}\right)^{-0.17} \tag{7}$$

where L_v is the distance between the inlet and outlet port centres. f is a function of Reynolds number and chevron angle.

Port Pressure drop is calculated as follows

$$\Delta P_p = 1.4 N_p \left(\frac{G_p^2}{2\rho}\right) \tag{8}$$

$$G_p = \frac{\frac{m}{\pi D_P^2}}{4} \tag{9}$$

and D_p is port diameter, which is part of plate specifications.

All the above calculations is repeated for the cold and hot fluid. Thus the total pressure drop over heat exchanger is calculated. The last step is to check heat transfer calculations to determine if design is acceptable.

The heat transfer calculations start with the calculation of the overall heat transfer coefficient with equation (10).

$$\frac{1}{U_f} = \frac{1}{h_c} + \frac{1}{h_h} + 1.2\left(R_{fh} + R_{fc}\right) \tag{10}$$

Where h_c and h_h the convective heat transfer coefficient is for cold and hot fluid. The R_{fh} and R_{fc} is the fouling factor. The required and actual heat duty can then be calculated using equation (11) and (12).

$$Q_R = mC_p(T_e - T_i) \tag{11}$$

$$Q_f = U_f A_e \Delta T_{lm} \tag{12}$$

A_e is the total developed area of all effective plates and ΔT_{lm} is the logarithmic temperature difference between two fluids.

The actual heat transfer is checked to be equal to Q_R and is known to be the design factor. We design for a factor of 1 and correct the actual flow rates due to the inclusion of fouling factors.

$$D_C = \frac{Q_f}{Q_R} \tag{13}$$

If this design factor is not achieved, the number of plates and number of passes is altered until optimal design is achieved.

The last step in the design process is to determine actual operating flow rates using equation (11) and the specified temperature.

Internal holding tank

For the internal holding tank, two main calculations were done. The first was to establish if it would be economically viable to use the internal holding tank instead of using heat exchangers. The second main calculation was to determine the required length of the pipe in the internal holding tank to get the required residence time for pasteurization. First, the transient heat transfer calculations were done.

The heat that needs to be added to the system can be calculated using

$$Q = mC_p(T_e - T_i) \tag{14}$$

Next, the external convective heat transfer coefficient, h_{ext}, is needed. If natural convection is assumed

$$h_{ext} = \frac{k_{water}Nu}{D} \tag{15}$$

where

$$Nu = \frac{0.6 + 0.387Ra^{\frac{1}{6}}}{\left(1 + \left(\frac{0.599}{P_r}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}} \tag{16}$$

Then the Rayleigh number, Ra, can be calculated using

$$Ra_L = \frac{g\beta(T_{inf} - T_s)D^3}{\mu^2 Pr} \tag{17}$$

Next, the internal convective heat transfer coefficient, h_{int}, is to be calculated using

$$h_{int} = \frac{k_{egg}Nu}{D} \tag{18}$$

where Nu is dependent on the type of flow. This system contains fully developed turbulent flow (seen by calculating the Reynolds number), and since the egg is being heated

$$Nu = 0.023Re^{0.8}Pr^{0.3} \tag{19}$$

where Re was calculated using

$$Re = \frac{354W}{d\mu} \tag{20}$$

Next, the length of pipe that is required to perform the necessary heat transfer is calculate using

$$L_{required} = \frac{A_{required}}{\pi D} \tag{21}$$

where

$$A_{required} = \frac{Q}{U\Delta T_{lm}} \tag{22}$$

U can be estimated by using

$$\frac{1}{U} = \frac{1}{h_{int}} + \frac{1}{h_{ext}} \tag{23}$$

ΔT_{lm} can be calculated by using two different assumptions. If it is assumed that T_s remains constant, the equation

$$\Delta T_{lm} = \frac{T_i - T_e}{\log\left(\frac{T_s - T_e}{T_s - T_i}\right)} \tag{24}$$

is used. Alternatively, it can be assumed that the liquid's temperature $\left(T_{inf}\right)$ in the tank remains constant. This will then make use of

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\log\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{25}$$

where

$$\Delta T_1 = T_{inf} - T_i \tag{26}$$

and

$$\Delta T_2 = T_{inf} - T_e \tag{27}$$

This concludes the transient heat transfer calculations. The steady state calculations are much easier. The length required for the desired residence time can be calculated using

$$L_{req} = \frac{Vt}{\frac{60\pi}{4}D^2} \tag{28}$$

To calculate the heat loss through the sides of the container, and therefore calculate the amount of heat to be added, basic heat transfer calculations must be performed. Since it is assumed that the system's heat transfer is at steady state

$$Q_{added} = Q_{convection} + Q_{radiation} \tag{29}$$

Equation (29) above assumes that no heat is lost through the lid on the top, or through the bottom to the ground. It is a good assumption, since these two areas can be insulated quite well. The relevant heat losses will then be calculated using

$$Q_{convection} = h_{tankwall}A(T_s - T_{inf}) \tag{30}$$

and

$$Q_{radiation} = \epsilon_{rad}\sigma A_s(T_s^4 - T_{surr}^4) \tag{31}$$

where $h_{tankwall}$ can be calculated using Equation (15) through to Equation (18) and substituting the physical properties of air at the given surrounding temperature.

Piping mechanical energy balances

The general form of the mechanical energy balance (MEB) is

$$\Delta P_{EP} + \Delta P_{EL} + \Delta P_{KE} + \Delta P_f' = \Delta P_a \tag{32}$$

where

$$\Delta P_f' = \Delta P_f + \Delta P_{EQ} + \Delta P_{CV} \tag{33}$$

ΔP_f can then be calculated using the Darcy Weisbach equation shown below.

$$\Delta P_f = \frac{62544 f' L W^2}{\rho d^5}\ kPa \tag{34}$$

where f' can be solved for using the Colebrook equation shown below.

$$\frac{1}{\sqrt{f'}} = -2\log\left(\frac{\epsilon/d}{3.7} + \frac{2.51}{Re\sqrt{f'}}\right) \tag{35}$$

where Re can be calculated using Equation (20). The Colebrook equation was solved using the IPython Notebook found at

https://github.com/WillemASmit/CIO_Group_6_Design.

An ϵ value of 0.013 mm was used.

Since the IHT has no elbows or other fittings, its ΔP_{EQ} is calculated by simply using Equation (34) for a pipe with the length of the tube inside the IHT.

Control valves and their tests

The basic method for selection of and sizing the control valves in the water lines are set forth by Greeff & Skinner (2000). The method is based upon 4 general rules for economical design. These rules should not be taken as law but serve as an indication of the most economical design. The rules are:

1(d) $\quad f(x)_d \leq 1$
1(n) $\quad f(x)_n \geq 0.1$
2(d) $\quad 0.25\Delta P_{stv,d} \leq \Delta P_{cv,d} \leq 0.5\Delta P_{stv,d}$
2(n) $\quad 0.5\Delta P_{stv,n} \leq \Delta P_{cv,n} \leq 1.5\Delta P_{stv,n}$

The design and maximum flow rates are achieved by increasing the nominal flow rate by set factor so that the flow rates are related by

$$\mathrm{W_d} = 1.05\, W_m = 1.15 W_n \tag{36}$$

The control valve is assumed to be fully open at the design flow rate. The pressure drop across the control valve is now calculated at the design flow rate using

$$V = C_{cv} f(x) \sqrt{\frac{\Delta P_{cv}}{SG}} \tag{37}$$

Where:

ΔP_{cv} = Pressure drop across the control valve in psi

$f(x)$ = The total fraction of the flow area of the valve available

V = Volumetric flow rate through the valve in GPM-USA

C_{cv} = The control valve characteristic as obtained from literature

Since we assumed that the valve will be fully open at the design flow rate the value for $f(x)_d$ is 1. Take note that this assumption will mean that rule 1(d) is automatically met

$\Delta P_{stv,n}$ and $\Delta P_{stv,m}$ is now calculated using equation (38). This can be done using proration or by re-calculating the system for the different flow rates. Proration simply adjusts for a new flow rate by multiplying ΔP_{stv} with the square of the ration of flow rates. Since proration is much faster and less resource intensive this method will be used. We can now check for rule 2(d)

$$\Delta P_{stv} = \Delta P_f + \Delta P_{EQ} + \Delta P_{KE} \tag{38}$$

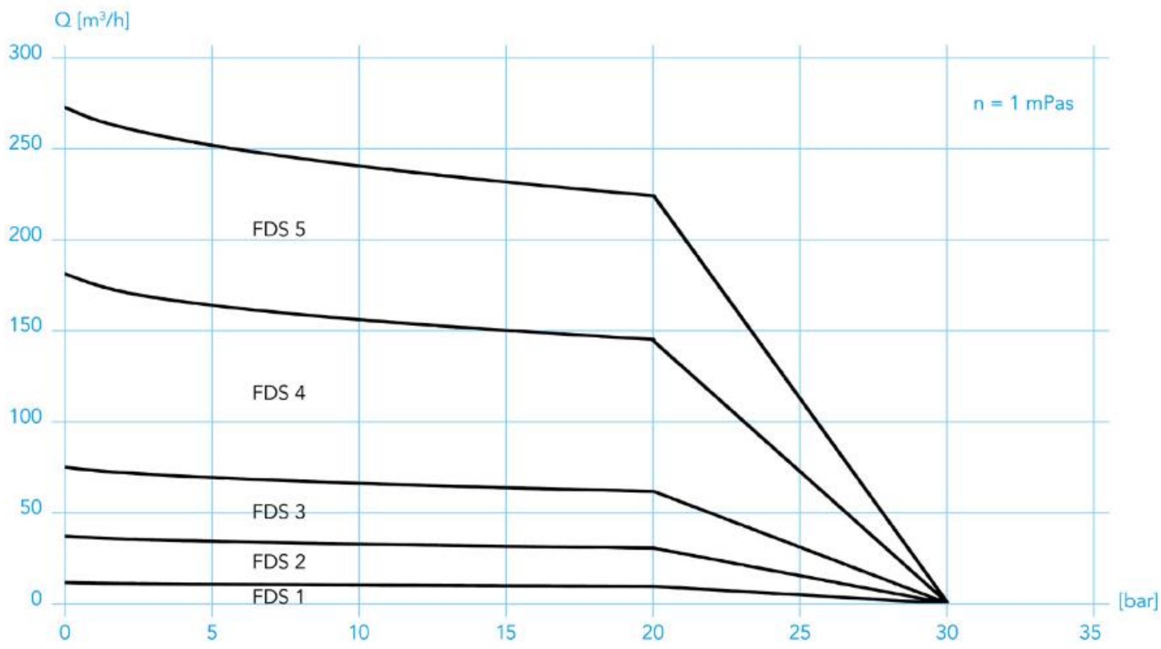
$\Delta P_{a,d}$ can now be calculated the MEB as specified in (32). Assuming $\Delta P_{a,v} = \Delta P_{a,d}$ we can now calculate $\Delta P_{cv,n}$ with the MEB as specified in Equation (32) and we validate rule 2(n). The validity of the assumption above is tested against the pump-curve and found to be reasonable for both the cooling and heating water lines After $\Delta P_{cv,n}$ is found the system can be adjusted if necessary.

Finally, $f(x)_n$ is calculated with Equation (37) and tested with rule 1(n). The system is adjusted and iterated until the correct valve size is found.

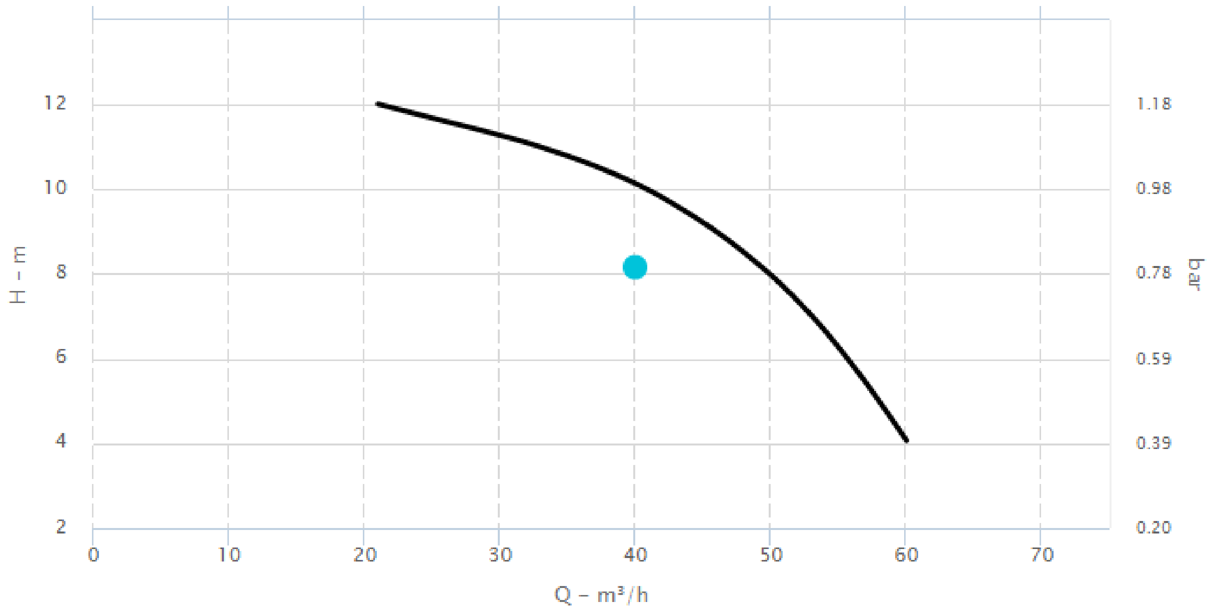
Take note that the entire process was programmed using Python in the Jupyter notebook environment.

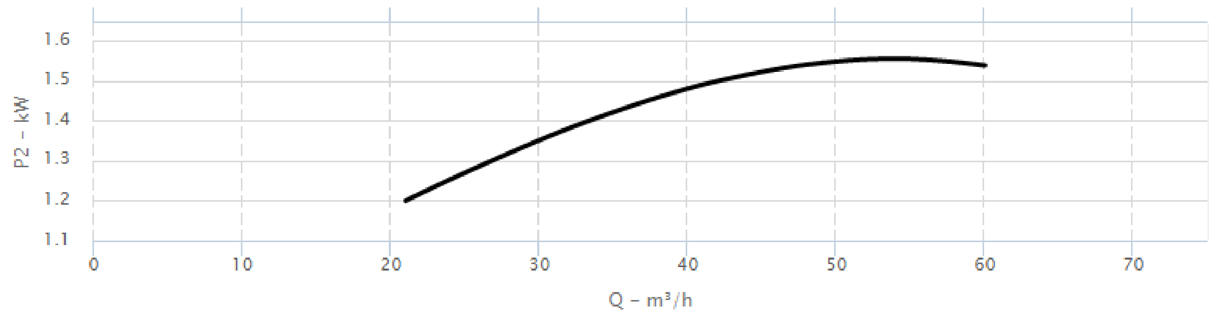
The result of the iteration of this process is used to find the control valve size.

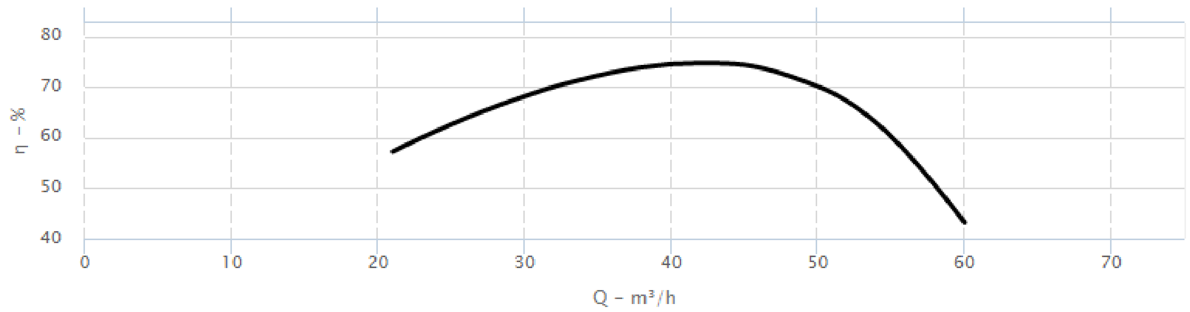
Twin Screw pump curve

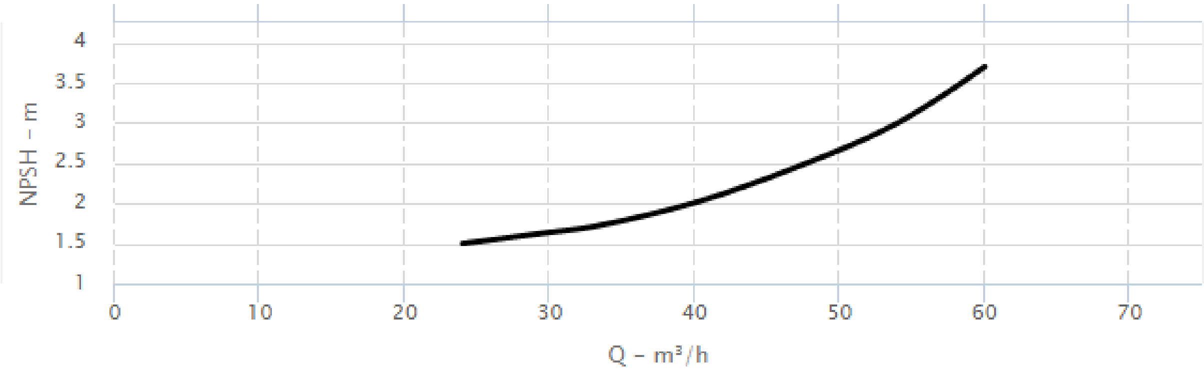


Centrifugal pump curves









NPSH - m
4
3.5
3
2.5
2
1.5
1
0
10
20
30
40
50
60
70
Q - m³/h