

Project 3: Design of Pasteurization System

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Introduction

Pasteurization is a process that involves heating up foods in order to kill harmful bacteria and pathogens. This project will explore the pasteurization of milk. It is important to precisely know the temperature and duration of the process in order to ensure the harmful bacteria is destroyed while the desirable enzymes and vitamins are not. In the words of professor Gucceri, the goal of Pasteurization is to kill the “bad guys” like bacteria and leave the “good guys” like enzymes and vitamins. For this project we will assume the milk will be exposed to a temperature of 73 °C for 17 seconds. The system will be able to Pasteurize 20,000 liters of milk per hour. All of the calculations will assume that milk has the same properties as water.

Process Configuration

System Design

For our process design, we have milk coming into our processing plant at 10°C. The pasteurization process happens as shown in the diagram below. The milk flows through a heat recovery heat exchanger that warms up the milk by cooling down the pasteurized milk. For our

design, we have decided that the milk after the heat recovery at point “A” will be at a temperature of 35°C. The milk will then go through the pasteurization process causing the milk to come out at point “B” at 73°C. The cooled pasteurized milk from point “C” has been decided to be at temperature 45 then goes through a cooler bringing the temperature down further to 25°C at point “D”. A chiller then cools down the milk to an exit temperature of 5°C where it is loaded into trucks for delivery.

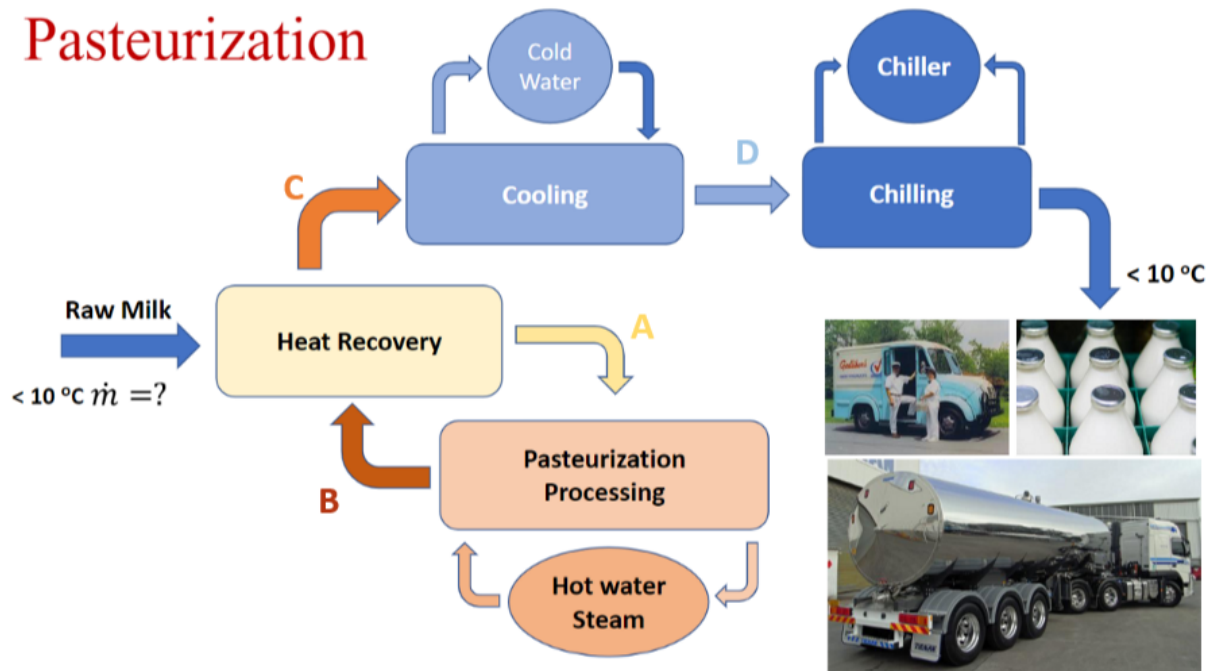


Figure 1. Block diagram of pasteurization process

For our project, an excel table was used to keep track of all of the variables and constants. Editing variables to get desired results was easy as the resulting calculator updates every time new parameters were entered. Each section of the sheet will be described in more detail in the following discussions, but the link to the excel sheet is in the table below for exploratory purposes. A zoomed-out view of our total table is shown in the figure below. The Yellow boxes are editable variables, the green are intermediary calculated variables, and the blue are desired ultimate outputs.

Excel Link	https://docs.google.com/spreadsheets/d/1nVxohjFC5IPpWQS5tSVjMVA28FnPHvWZ-PMkoA_Mdok/edit?usp=sharing
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Table 1. Spreadsheet link

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1																	
2		Parameter		Temp (Celsius)		Time for Pasteurization		17 (seconds)			Flowrate (Liters per hour)		20000				
3		Raw milk input temperature		10							Kg per hour		20000				
4		Temperature after heat recovery		35							Kg per second		5.555555556				
5		Temperature of pasteurization		73													
6		Temp after heat recovery (loss)		45													
7		Temperature after cooler		25													
8		Temperature after chiller		5													
9																	
10																	
11																	
12		First exchanger: Heat recovery system (calculated w/ LMTD)															
13		Overall heat transfer (U):		2000		Watts per m ² degree K											
14		Delta T1 (Celsius/Kelvin)		53		K											
15		Delta T2 (Celsius/Kelvin)		10		K											
16		Heat flow into milk (Q, watts)		551111.1111		Watts											
17		LMTD:															
18		Logarithmic mean:		18.79574514		degrees											
19		Area between fluids (meters ²)		10.08022493		square meters											
20																	
21																	
22																	
23																	
24																	
25		Second exchanger: Heating for Pasteurization (Calculated with the exponential equation)															
26		Overall heat transfer (U):		2000		Watts per m ² degree K											
27		Hot water bath temp (C)		100		degrees C											
28		In of dimensionless temperature		-0.8789504039													
29		Uavg / mass flowrate * Cp		0.08904209501													
30																	
31		Area between fluids (meters ²)		10.21070803		square meters											
32																	
33																	
34																	
35																	
36		Third exchanger: Pre chiller cooling with room temp water (Calculated with the exponential equation)															
37		Overall heat transfer (U):		2000		Watts per m ² degree K											
38		Cool water bath temp (C)		23		degrees C											
39		Intermediate calculation		-2.039881927													
40		Intermediate calculation		0.08904209501													
41																	
42		Area between fluids (meters ²)		23.8730944		square meters											
43																	
44																	
45																	
46																	
47		Fourth exchanger: Ice bath chiller (Calculated with the exponential equation)															
48		Overall heat transfer (U):		2000		Watts per m ² degree K											
49		Cool water bath temp (C)		0		degrees C											
50		Intermediate calculation		-1.809437912													
51		Intermediate calculation		0.08904209501													
52																	
53		Area between fluids (meters ²)		18.70924507		square meters											
54																	
55																	
56																	

Figure 2. Excel spreadsheet of input parameters and calculations

Assumptions

For our project we made the following assumptions:

- The tubes between heat exchangers are insulated, i.e. no heat loss
- The tubes in the heat exchangers are thin-walled, meaning there is no resistance to heat flow due to conductivity
- There is 5m of insulated pipe between each of the heat exchangers
- The heat capacity of milk is the same as that of water
- The density of milk is the same as water
- The overall heat transfer was assumed to be 2000 in each heat exchanger
- Tubes are made out of stainless steel and have a surface roughness of 0.1 mm

Heat Exchanger Design

In our system, the surface area for the heat recovery heat exchanger was calculated with LMTD. The surface areas for the Pasteurization heater, pre-chiller cooler, and chiller were all calculated with the exponential equation for constant T_{∞} .

$$Q = UA \left(\frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2 / \Delta T_1)} \right)$$

Equation 1. LMTD method of finding heat exchanger surface area

$$\frac{T_{\infty} - T_{m,o}}{T_{\infty} - T_{m,i}} = \exp\left(\frac{-U * A_s}{m * C_p}\right)$$

Equation 2. Exponential method of finding heat exchanger surface area

Our team created a spreadsheet to automate calculation and allow for easy checking of multiple design configurations. Below is our set of temperature parameters that we decided on for our Pasteurization system.

Parameter	Temp (Celsius)
Raw milk input temperature	10
Temperature after heat recovery	35
Temperature of pasteurization	73
Temp after heat recovery (loss)	45
Temperature after cooler	25
Temperature after chiller	5

Figure 3. Table of temperature parameters

We assumed an overall heat transfer coefficient of 2000 with no thermal resistances due to wall thickness or fouling. Below is the table showing our calculations for the heat recovery system. Yellow boxes are editable design parameters that the user can change, green boxes are intermediate values needed to find the final answer, and the blue boxes contain the final output of our calculations.

Heat Exchanger 1: Heat Recovery

First exchanger: Heat recovery system (calculated w LMTD)		
Overall heat transfer (U):	2000	Watts per m ² degree K
Delta T1 (Celsius/Kelvin)	63	K
Delta T2 (Celsius/Kelvin)	10	K
Heat flow into milk (Q, watts)	581111.1111	Watts
LMTD:		
Logarithmic mean:	28.79574614	degrees
Area between fluids (meters ²)	10.09022493	square meters

Figure 4. Table of LMTD calculations for first exchanger

In this case, the heat recovery system needs to have about 10 square meters of contact area for both of the fluids.

Pipes for exchanger 1:		
Number of pipes in parallel	20	pipes
Diameter in meters	0.03	meters
Perimeter	0.0942	meters
Total length required	107.1149143	meters
Length needed per pipe	5.355745716	meters

Figure 5. Table of pipe calculations for first exchanger

In order to ensure the temperature distribution of the milk was mostly constant throughout the pipe, we used small diameter pipes with a diameter of 3 centimeters. This also keeps the Reynolds number high enough to ensure turbulent flow. We allowed the user to change the number of pipes and the pipe diameter in our table, and we designed each exchanger to have a length per pipe of between 5 and 7 meters. In a single pass shell and tube exchanger, the overall footprint of the exchanger is roughly half of the average length needed per pipe. This would make each exchanger between 2.5 and 3.5 meters long, which can easily fit inside of a standard 53 foot truck bay.

Heat Exchanger 2: Heating for Pasteurization

The second heat exchanger heats the incoming milk from 35 degrees celsius up to 73 degrees, where it remains at that temperature for 17 seconds. The table of calculations is below.

Second exchanger: Heating for Pasteurization (Calculated with the exponential equation)			
Overall heat transfer (U):	2000	Watts per m ² degree K	
Hot water bath temp (C)	100	degrees C	
In of dimensionless temperature	-0.8785504039		
Uavg / mass flowrate * Cp	-0.08604206501		
Area between fluids (meters ²)	10.21070803	square meters	

Figure 6. Table of exponential equation calculations for second exchanger

Pipes for exchanger 2:		
Number of pipes in parallel	20	pipes
Diameter in meters	0.03	meters
Perimeter	0.0942	meters
Total length required	108.3939281	meters
Length needed per pipe	5.419696405	meters

Figure 7. Table of first iteration pipe calculations for second exchanger

On the way to the heat recovery system, the heated milk must be allowed to sit for 17 seconds before it exchanges its heat with incoming raw milk. We set a target pipe length of 10 meters and determined the diameter based on this target length and the mass flow rate, and ended up with a required pipe diameter of 10.96 centimeters.

Pipe from Pasteurizer to heat recovery system:		
Target length of transfer pipe	10	meters
Mean velocity requirement	0.5882352941	m/s
Pipe area to meet velocity req	0.009444444444	sq. meters
Pipe radius	0.05484327538	meters
Pipe diameter required	0.1096865508	meters
Pipe diameter required	10.96865508	centimeters

Figure 8. Table of pipe calculations for heating system

Heat Exchanger 3: Cooler

For the pre-chiller section, we calculated the exchanger area assuming a bath temperature of 22°C. The exchanger takes in milk at 45 degrees and cools it to 25°C for the chiller.

Third exchanger: Pre chiller cooling (Calculated with the exponential equation)			
Overall heat transfer (U):	2000	Watts per m ² degree K	
Cool water bath temp (C)	22	degrees C	
In of dimensionless temperature	-2.036881927		
Uavg / mass flowrate * Cp	-0.08604206501		
Area between fluids (meters ²)	23.6730944	square meters	

Figure 9. Table of exponential equation calculations for the third exchanger

Because the temperature change is much larger than in other sections of the Pasteurization system, the required surface area is much higher, at 23.6 square meters. To keep the overall footprint of the exchanger similar to the others, we doubled the number of pipes in the exchanger.

Pipes for exchanger 2:		
Number of pipes in parallel	40	pipes
Diameter in meters	0.03	meters
Perimeter	0.0942	meters
Total length required	251.3067346	meters
Length needed per pipe	6.282668365	meters

Figure 10. Table of second iteration pipe calculations for second exchanger

Heat Exchanger 4: Chiller

The final exchanger is the chiller, which takes in milk at 25°C and cools it to 5°C for bottling. The exchanger uses an ice bath at 0°C.

Fourth exchanger: Ice bath chiller (Calculated with the exponential equation)			
Overall heat transfer (U):	2000	Watts per m ² degree K	
Cool water bath temp (C)	0	degrees C	
In of dimensionless temperature	-1.609437912		
Uavg / mass flowrate * Cp	-0.08604206501		
Area between fluids (meters ²)	18.70524507	square meters	

Figure 11. Table of calculations for fourth exchanger

Pipes for exchanger 2:		
Number of pipes in parallel	35	pipes
Diameter in meters	0.03	meters
Perimeter	0.0942	meters
Total length required	198.5694806	meters
Length needed per pipe	5.673413731	meters

Figure 12. Table of third iteration pipe calculations for the second exchanger

The surface area required for the chiller was high, but not as high as the pre chiller cooling exchanger. We set the number of pipes to 35 for this exchanger, which makes the exchanger approximately 10 feet long.

Pumps

The total distance milk must travel to pass through our system is the sum of all the pipe lengths in the exchangers added to the lengths of pipe between the exchangers. We assumed a distance of 5 meters between each exchanger and a diameter of 10 cm for all transfer pipes except the one immediately after the Pasteurization heater.

The equation for the change of pressure in a pipe is shown below.

$$\Delta P = 8 f \frac{\dot{m}^2 L}{\rho \pi^2 D^5}$$

Figure 13. Change in pressure equation

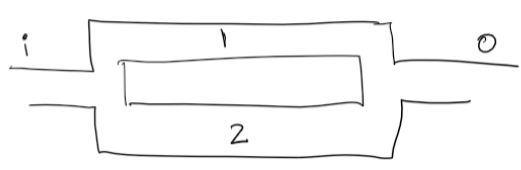
The equation for needed pump power considering a known change in pressure is shown below.

$$\text{Pump power} = \frac{\dot{m}}{\rho} \Delta P$$

Figure 14. Pump power equation

To find the pressure drop across the heat exchangers with many equal length and size tubes it was desired to find an easy conversion factor. In the calculations performed below is it visible that the pressure drop across many tubes is equal to the respective pressure drop across a single tube of equal size divided by the number of tubes squared.

For Parallel tube flow



$$Q_i = Q_o \quad Q = \frac{v d^2 \pi}{4} \quad v^2 = \left(\frac{Q 4}{d^2 \pi} \right)^2$$

$$h = \frac{4 f l v^2}{2 g d} = \frac{4 f l Q^2 4^2}{2 g d^5 \pi^2}$$

$$h = \frac{f l Q^2}{3.025 d^5} \quad Q_i = Q_1 + Q_2 \quad f_1 = f_2 \quad l_1 = l_2 \quad d_1 = d_2$$

$$h_1 = h_2 \quad \frac{f_1 l_1 Q_1^2}{3.025 d_1^5} = \frac{f_2 l_2 Q_2^2}{3.025 d_1^5} \quad Q_1 = Q_2 \quad Q_i = Q_{i/2}$$

$$h_{\text{single}} = \frac{f l (Q_i)^2}{3.025 d^5} \quad h_{\text{parallel}} = \frac{f l \left(\frac{Q_i}{n} \right)^2}{3.025 d^5}$$

$$\frac{h_{\text{single}}}{n^2} = h_{\text{parallel}} \quad \Delta P = h 9800 \quad \frac{\Delta P_{\text{single}}}{n^2} = \Delta P_{\text{parallel}}$$

Figure 15. Parallel tube pressure analysis

We constructed a table to calculate all the pressure drops for each section of our system. The table is pasted below.

Change of Pressure:								
	Friction Factor	Mass Flow Rate (kg/s)	Length of Pipe (m)	Density (kg/m ³)	Diameter (m)	N pipes	ΔP (Pa)	watts needed
from raw output	0.03	5.56	5	1000	0.03	1	154676.9301	858.4569619
heat recovery 1	0.03	5.56	5.36	1000	0.03	20	414.5341726	2.300664658
transfer pipe	0.03	5.56	5	1000	0.03	1	154676.9301	858.4569619
milk heater	0.03	5.56	5.42	1000	0.03	20	419.1744805	2.326418367
to heat recovery	0.03	5.56	10	1000	0.11	1	466.7651118	2.59054637
heat recovery 2	0.03	5.56	5.36	1000	0.03	20	414.5341726	2.300664658
to pre-chiller	0.03	5.56	5	1000	0.03	1	154676.9301	858.4569619
pre-chiller	0.03	5.56	6.28	1000	0.03	40	121.4213901	0.6738887151
to chiller	0.03	5.56	5	1000	0.03	1	154676.9301	858.4569619
chiller	0.03	5.56	5.67	1000	0.03	35	143.1866438	0.7946858733
chiller exit	0.03	5.56	5	1000	0.0942	1	506.7308014	2.812355948

Figure 16. Table of pressure drop and power calculations

The total power required to pump the milk through at 5.55 KG/s (20000 Liters/hour) is 3.447 kilowatts, or 4.69 horsepower.

Cost Analysis

By using the heat-recovery heat exchanger in our system we were able to save energy. This reduction in energy consumption results in less cost for Pasteurization. The hot liquid coming out of the Pasteurizer at 73°C heats up the cool liquid coming in at 10°C. More energy in the form of using an electric heater would have otherwise had to go into heating up the incoming milk to higher temperatures. The total energy transfer from the hot milk into the cold milk was calculated previously to be 581 kW. The cost savings were then calculated by using a base cost of 0.15 \$/kW-hr to be \$763,580 per year. This is all shown in the table below. As shown below a cost savings of close to 40% is a huge amount considering such a large-scale plant that was designed.

Savings from using a heat recovery system:		
kW hours recovered per day	13946.66667	kWH
kW hours recovered per year	5090533.333	kWH
Savings assuming 15 cents/kWH	763580	dollars
Without using heat recovery system:		
kWH used for heating per day:	35145.6	kWH
kWH used for heating per year:	12828144	kWH
Heating associated costs:	1924221.6	dollars
Annual heating bill w/o recovery:		
	1.9242216	million dollars
Annual heating bill with recovery:		
	1.1606416	million dollars
Percent cut to heating bill:	39.68	percent reduction in cost

Figure 17. Cost savings calculations

Conclusion

In this project, we learned how to use LMTD and exponential methods to calculate heat exchanger surface areas for a Pasteurization system. We also learned how to set up an excel spreadsheet in order to quickly assess different design parameters for the heat exchangers. We learned about the importance of heat exchangers in agricultural, chemical, and pharmaceutical industries. We also learned about heat exchangers serving as an alternative to batch processing in order to scale projects up for mass production.

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Works Cited

Guceri, S. (2022, February 20). Project-3 Heat Exchangers and Pasteurization