ME4429 Project #2 - Milk Pasteurization

By

Nathan Lipka

Kellen Queeney

David Strom

Date:

February 26th, 2024

Report Submitted to:

Professor Selcuk Guceri

Authors

Nathan Lipka

I am a soon-to-be WPI Mechanical Engineering graduate, business owner, and pet owner. I have experience designing various things during my time at WPI including a project with iRobot. My goal is to one day create a revolutionary product that I can start a new business with.

Kellen Queeney

My name is Kellen, I am pursuing a Mechanical Engineering degree at WPI after transferring from UMass Amherst. Ever since I first started robotics back in high school, I have always had a drive to create, and a hunger to learn more. I hope to one day create a product that can have a positive impact on everyone's lives.

David Strom

I am a sophomore Mechanical Engineering student who is on track to graduate with my master's in 4 years. I have always loved the design and optimization process, giving me the ambition to design and make things. My goal is to design and patent innovative products and designs.

Technical Description

This short paper documents our HTST (High-Temperature Short-Time) design for a milk pasteurization device which will be able to pasteurize 20,000 liters per hour. The process of pasteurization eliminates any harmful bacteria such as Salmonella, E. coli, or Listeria as well as extending the shelf life of the milk. Milk is pasteurized after being heated up to 73 degrees C for 17 seconds. After the process is complete the milk is cooled to under 10 degrees C to prevent any other heat-related changes from occurring, rendering the milk unsafe for human consumption.

Schematics

Figure 1 displays a flow chart documenting the entire pasteurization process from start to finish. The milk enters the system under 10 degrees C which enters the heat recovery chamber, this section is purpose-built to utilize extra heat from the pasteurization process in order to preheat the incoming cold milk while the pasteurized milk passes to be cooled. While the milk is in the pasteurization process hot steam is used to evenly heat the milk within the internal pipes. These pipes are internally finned in order to create a spiral flow which allows for an even heating of the milk. Once in the cooling section, cold water is used to cool the milk (again within smaller internal pipes). Next is the chiller which reduces the temperature to under 10 degrees C where it is then packaged and ready for the customer.

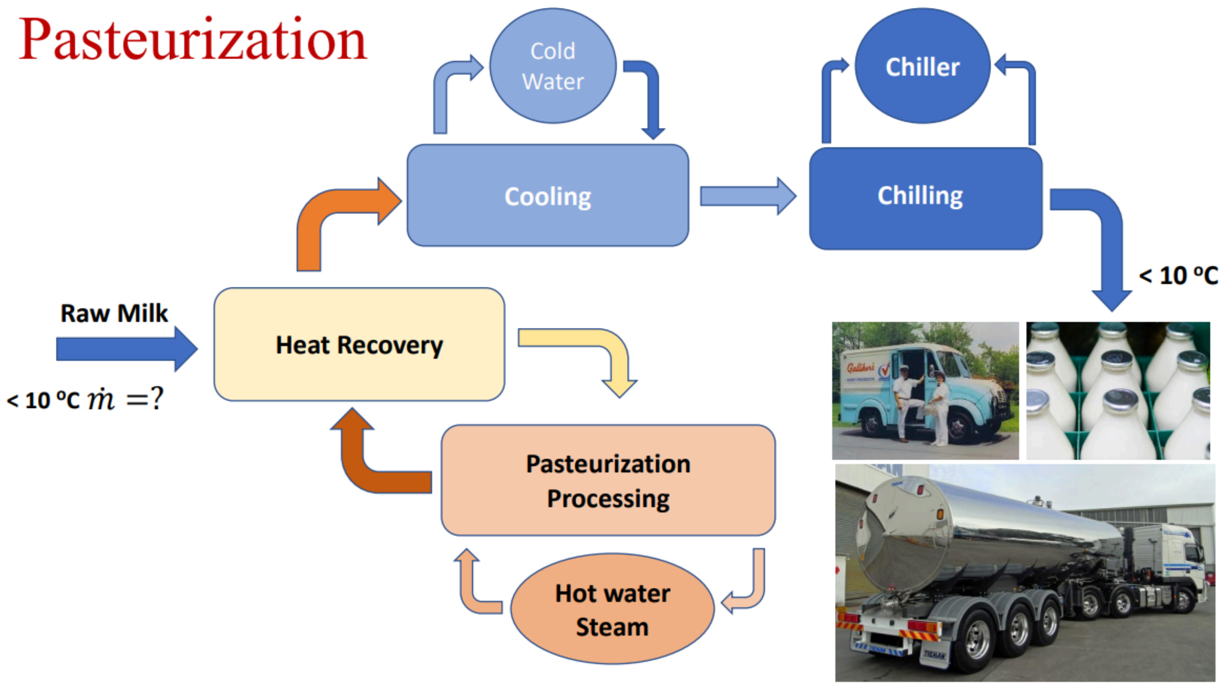


Figure 1: Pasteurization System Flow Chart

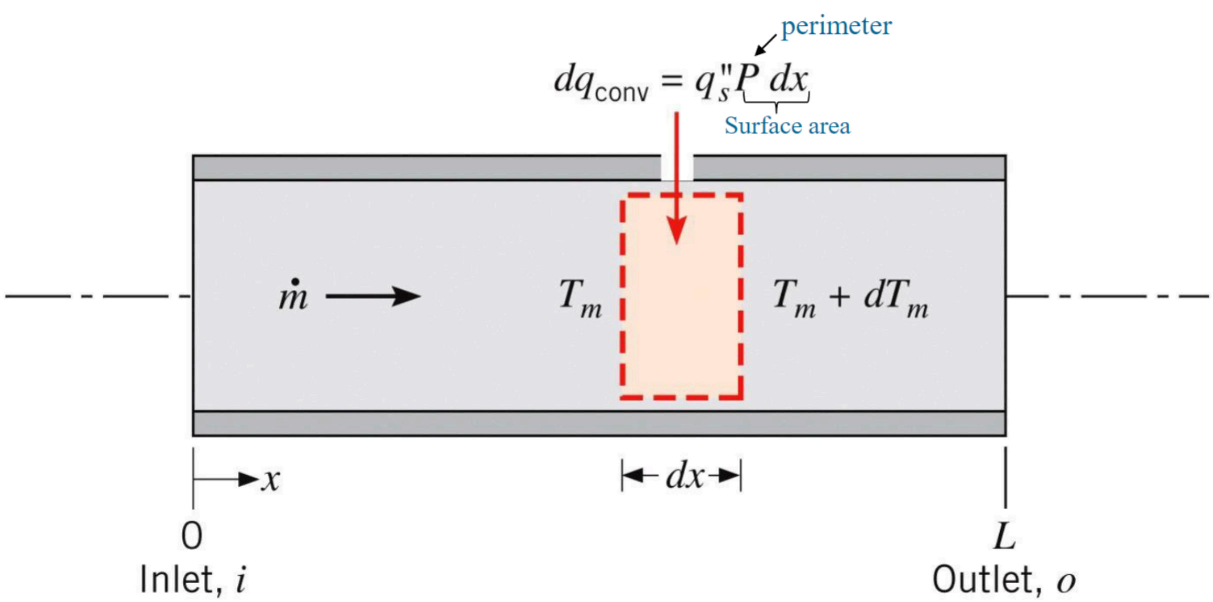


Figure 2: Internal Flow Heat Transfer Heat Balance Diagram

<u>Formulas</u>

Heat Exchange in Pipe/Coil Flows

$$\frac{dT_m}{dx} = -\frac{d(\Delta T)}{dx} = \frac{P}{\dot{m}c_p} h\,\Delta T \;\rightarrow\; \int_{\Delta T_i}^{\Delta T_o} \frac{d(\Delta T)}{\Delta T} = \frac{P}{\dot{m}c_p} \int_0^L h\,dx$$

$$ln\frac{\Delta T_o}{\Delta T_i} = -\frac{PL}{\dot{m}c_p}\left[\frac{1}{L}\int_0^L h\,dx\right] = -\frac{PL}{\dot{m}c_p}\bar{h}_L$$

If we have the constant wall temperature:

$$\frac{\Delta T_o}{\Delta T_i} = \frac{T_s - T_{m,o}}{T_s - T_{m,i}} = exp\left[-\frac{PL}{\dot{m}c_p}\bar{h}\right]$$

If we have a pipe/coil flow through an external fluid and with an overall heat transfer coefficient of U between the two fluids:

$A_s = \pi DL$

$$\frac{\Delta T_o}{\Delta T_i} = \frac{T_\infty - T_{m,o}}{T_\infty - T_{m,i}} = exp\left[-\frac{\bar{U}A_s}{\dot{m}c_p}\right]$$

Turbulent Internal Flows:

$$Nu_D = 0.023\,Re_D^{4/5}\,Pr^n$$

Most commonly used

$n = 0.4$ *heating*

$n = 0.3$ *cooling*

$$Nu_D = 0.027\,Re_D^{4/5}\,Pr^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

Large viscosity variations like in oils

$$Nu_D = \frac{\left(f/8\right)(Re_D - 1{,}000)\,Pr}{1 + 12.7\left(f/8\right)^{0.5}\left(Pr^{1/3} - 1\right)}$$

More accurate but more complicated

$$where \qquad f = [0.790\, ln(Re_D) - 1.64]^{-2}$$

Pressure Loss:

$$f = \frac{-(dp/dx)\,D}{\rho\, u_m^2/2}$$

Laminar:

$$f = \frac{64}{Re_D}$$

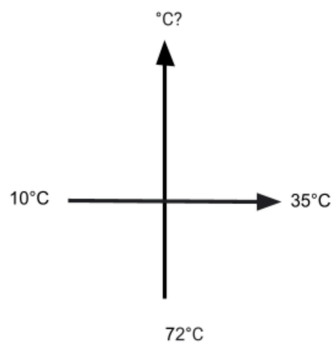
Turbulent:

$$f = (0.790 \ln Re_D - 1.64)$$

$$\Delta p = f\,\frac{\rho u_m^2}{2D}(x_2 - x_1)$$

Cold Milk Enters Regenerator:

Cp = 3890 *J KgK*
Tc, *i* = 10°*C*
*T*h,*u* = 72°*C*
Tc, *o* = 35°*C*
*T*h, *o* =? °*C*



Calculations

$Q = \dot{m} Cp \Delta T$

$Q = 5.796*3980*(10-35)$

$Q = 563661$ *watts at regenerator*

$NTU = 1/Cr-1 * ln(\ \varepsilon-1 * \varepsilon Cr-1)$

$Cr = Cmin/\ Cmax$

Cp=3980J/KgK

Cpatm= 3770J/KgK

$Cc = \dot{m} Cp$

$Cc = 5.796 * 3980$

$Cmax = C = 23{,}068.08\ J\ c\ sK$

$Ch = \dot{m} Cp\text{h}$

$Ch = 5.796 * 3770$

Cmin=C =21,850.92 J h/sK

$Cr = Cmin/\ Cmax$

$Cr = 21{,}850.92/\ 23{,}068.08$

$Cr = 0.94724$

$\varepsilon = q/qmax$

$q = 563,\ 661$ *watts*

$qmax = Cmin\ (T\text{ho} - Tci)$

$qmax = 21,\ 850.\ 92(72 - 10)$

$qmax = 1,\ 354,\ 757.\ 04$ *watts*

$\varepsilon = 563{,}661/\ 1{,}354{,}757.04$

$\varepsilon = 0.416$

$NTU = 1/(Cr-1)\ ln(\ \varepsilon-1/\ \varepsilon Cr-1\ )$

$NTU = 1/(0.94724-1)\ ln((\ 0.416-1\ )\ /((0.416*0.94724)-1))$

$NTU = 0.69978 \simeq 0.7$

$NTU = UA/Cr$

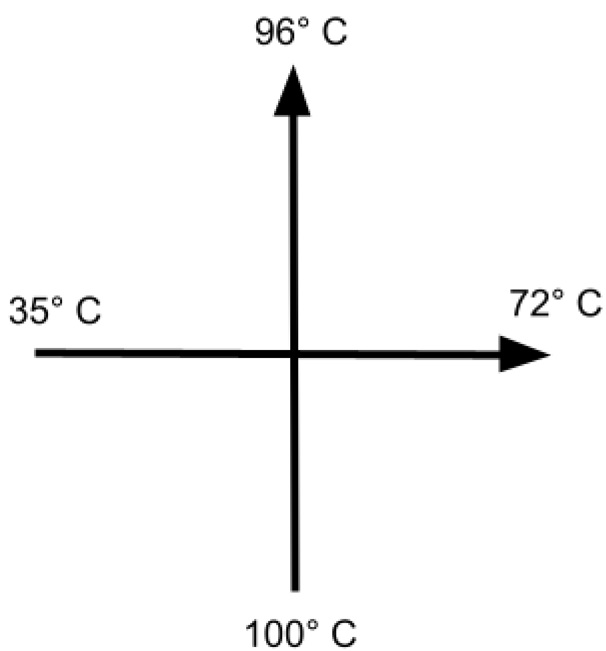
$A = ((NTU)(Cmin))/\ U$

$A = ((0.7)(21{,}850.92)\ )/2000$

$A = 7.64m2$
Volumetric flow rate : 0. 0056 m^3/s
$Length = 2m$
$OuterDiameter = 0.2m$
$Crosssectionofarea = 0.031416m2$
$Circumference = \Pi(d)$
$Circumference = \Pi(0.2)$
$Circumference = 0.628$m

$Velocity = 0.0056/ 0.031416m2$
$Velocity = 0.178\ ms$
$Areaofonepipe = 0.628 * 0.2m$
Area of one pipe = 0.1256
Pipes required = 7.64/.1256
Pipes required = 61

Internal Flow Of Pasteurization:



$\epsilon = 0.8$ $m = 5.76\, Kg/s$ Cc = mCp
$Cc = 5.796 * 4,110$ $Cmax = Cc = 23,670\, J/sK$
$Ch = mCph = 5.796 * 4,040$
$Cmin = Ch = 23,270\, J/sK$

$Cr = Cmin/Cmax = 23,270/23,670 = 0.9831$

$NTU = \frac{1}{Cr-1} ln(\frac{\epsilon-1}{\epsilon Cr-1}) = \frac{1}{0.9831-1} ln(\frac{0.8-1}{0.8*0.9831-1}) = 3.4427 = \frac{UA}{Cr}$

$A = \frac{(NTU)(Cmin)}{U} = \frac{(3.4427)(23,270)}{2000} = 40.056m^2$ for pasteurization

$q = \epsilon Cmin(Tho - Tci) = 0.8 * 23,270(100 - 35) = 1,210,040\, watts$

Volumetric flow rate: $0.0056\, m^3/s$ Length = 2 m Diameter = 0.2 m

Crosssectionofarea = 0.031416 m^2
Circumference = $\Pi(d)$
Circumference = $\Pi(0.2)$
Circumference = 0.628m
Velocity = 0.0056/ 0.031416$m2$
Velocity = 0. 178 *ms*
Areaofonepipe = 0.628 * 0.2m
Area of one pipe = 0.1256
Pipes required = 12.025401 /.1256
Pipes required = 96 pipes

Chilling Chamber:

ε = 0. 5

ṁ = 5. 76 Kg/s

C_max = C_c = ṁCp = 5. 796 * 4, 200 = 24, 192 J/sK

C_min = C_h = ṁCp_h = 5. 796 * 4184 = 24, 099 J/sK

Cr = (C_min)/(C_max) = 24,099/24,192 = 0.996

NTU = 3. 11 = UA/Cmin

A = (NTU)(C_min)/U = (0.998)(24,099)/2000

A = 12.025401 m^2

q = εC_min (T_ho − T_ci) = 0. 5 * 24, 099(45 − 5) = 481,980 watts

A = 12.025401 *m*^2

Volumetric flow rate : 0. 0056 *m*^3/*s*

Length = 2 *m*

OuterDiameter = 0.2 *m*

Crosssectional area= 0.031416 *m*^2

Circumference = Π(*d*)

Circumference = Π(0. 2)

Circumference = 0.628 m

Velocity = 0.0056/0.031416 *m*^2

Velocity = 0. 178 *m/s*

Areaofonepipe = 0.628 * 0.2

Area of one pipe = 0.1256 m^2

Pipes required = 12.025401/.1256

Pipes required = 96 pipes

Reynolds

Chilling = 1.035 x .178 x 30.5/.002158 = 2603.81

Heater = 1.035 x .178 x 48/.002158 = 4.097.79

Regenerator = 1.035 x .178 x 48/.002158 = 4.097.79

Head Loss

h = f(L/D)(v^2/2g)

h_Regeneration= (0. 04(61*0.5)/.3)*(.178^2)/2(9.81)

h_Regeneration = 0. 00657m

h_Pasteurization = (0. 043(96*2)/.3)*(.178^2)/2(9.81)

h_Pasteurization = .0444m

h_Chilling = (0.083(96*2)/.3)*(.178^2)/2(9.81)

h_Chilling = .0858m

Total head lost = 0.13677 m

Cost savings for regenerator

Cost Savings = W/1000 * c = 563661/1000 * .15 = $84.55