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Process Control of Milk Pasteurization using Geothermal Brine with Proportional Controller

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ABSTRACT

Geothermal brine can be used as a heating liquid for pasteurization unit either by directly use the brine to heat up the raw milk, or by heating secondary fresh water. The geothermal brine can be obtained directly from geothermal well or from geothermal power plant separator. Unlike conventional pasteurization, the flow rate and temperature of geothermal brine might fluctuate due to many factors such as rain, well decline, and well shut down. Inherently the geothermal reservoir tends to decline in pressure and temperature. If the geothermal brine is obtained from geothermal power plant, then the flow rate and temperature of geothermal brine itself is susceptible to many changes in plant's operation. A control system is needed for such utilization of geothermal brine. Simulation has been carried out to study the effect of proportional control under heating fluid temperature disturbance. The result shows that proportional control could be used to compensate such disturbance. The proportional controller controls milk inlet flow rate to balance the effect of hot water temperature reduction.

1. INTRODUCTION

Pasteurization is a mild (as opposed to frying, baking or roasting) heat treatment which aims to fulfill two purposes, to remove pathogenic bacteria from foods, thereby preventing disease, and to remove spoilage (souring) bacteria to improve its keeping quality (Lewis, M.J., 2006). Pasteurization process can be done to various kind of food and beverage products, such as tomato juice, honey, ice cream mix, and including milk. Each food has different temperature and time for pasteurization process. Table 1 shows temperature and time used in pasteurization for various food product. International Dairy Federation define pasteurization as follows: "pasteurization is a process applied to a product with the objective of minimizing possible health hazards arising from pathogenic microorganisms associated with the product (milk) which is consistent with minimal chemical, physical and organoleptic changes in the product". Pasteurization does not inactivate all microorganisms: those which survive pasteurization are termed thermodurics, and those which survive a harsher treatment (80-100ºC for 30 minutes) are termed spore formers (Smith, P.G., 2011).

Food Material	Temperature (ºC)	Time (s)
Milk	72	15
Ice cream mix	80	20
Tomato juice	118	60
Honey	71	300
Fruit juice	88	15
Soft drinks	95	10

Table 1: Typical treatment temperature and time in pasteurization (Smith, P.G., 2011)

Pasteurization can be accomplished by a combination of time and temperature, such as (i) heating the milk to a relatively lower temperature and maintaining it for a longer time, or (ii) heating milk to a high temperature and holding it for a short time only (Ramesh, 2007). Pasteurization could be done by heating the milk stream using heating equipment such as heat exchanger, or heating the already packaged milk (in-container pasteurization). In-container pasteurization usually utilize hot water bath or steam / hot water spray. Hot water bath pasteurizers use a conveyor belt which moves through a tank at a specified speed to provide adequate time in the bath to accomplish pasteurization. Steam / hot water pasteurizers use a conveyor belt or any conveying equipment to move the milk container into various heating and cooling section.

Pasteurization of unpacked milk also could be done in several ways which vary according to combination of time (duration) and temperature of pasteurization process. Vat pasteurization is basically a batch process that uses a tank-type heat exchanger to heat the milk and then hold it for a relatively long duration. This process is well suited for small scale production but not for large scale production because batch processes is inherently slow. Although it is possible to add more vats to increase production capacity, the process will still suffer from complicated and expensive process control (Ramesh, 2007).

Continuous pasteurization of unpacked milk for large scale production usually uses heat exchanger as heating equipment with fuel-heated hot water or steam as heating medium. The advantages of heat exchanger over in-container processing include (i) more uniform heat treatment, (ii) simpler equipment and lower maintenance costs, (iii) reduced space requirement and labor costs, (iv) greater flexibility for different products, and (v) greater control over pasteurization conditions (Ramesh, 2007). Heat exchanger also gives lower operating costs over batch processes due to ability to control and operate the process entirely automatic. There are several number of continuous pasteurization method, for example high-temperature-short-time (HTST) pasteurization, Flash pasteurization, and Ultra-High-Temperature (UHT) pasteurization.

1.2 HTST Pasteurization

HTST pasteurization is a continuous flow system using tubular, plate, swept surface, direct steam, in conjunction with a timing pump, a holder, and controls for temperature and flow rate (Ramesh, 2007). HTST pasteurizers usually apply regenerative heating to achieve a more economical operation. Typical temperature for HTST pasteurization is 72ºC for 15 seconds with temperature tolerance ±0.5ºC (Smith, 2011).

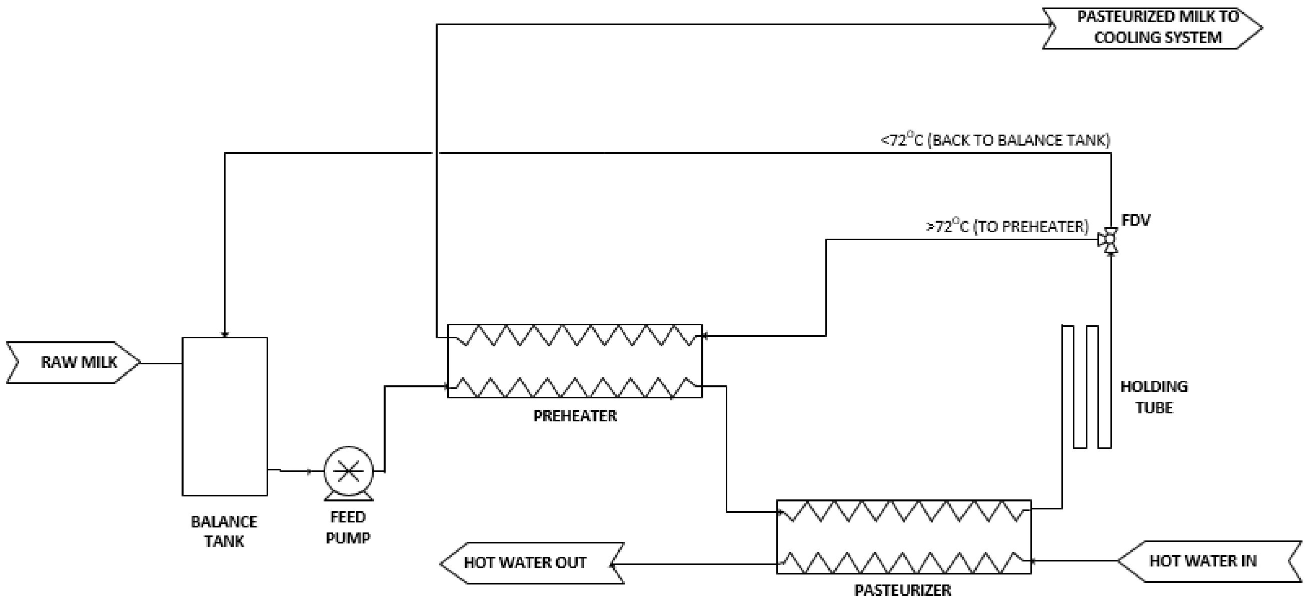

Figure 1: Typical HTST pasteurization process (reworked from Lewis, M.J., 2006)

Figure 1 shows a process flow diagram of an HTST pasteurization. Flow of feed stream is regulated by a metering pump, usually piston or rotary pump. The holder gives provide holding time for the milk stream to stay on a certain temperature at an intended duration. Insulated tank or pipe / tube could be use as the holder. Temperature is regulated by Flow Diversion Valve (FDV) and temperature sensor. FDV is a remotely activated valve located downstream from the holding tube. Flow is maintained forward if the milk stream coming out of heat exchanger is above the desired temperature. If temperature sensor detects milk stream temperature below desired temperature range, the FDV will diverts the flow back to the balance tank.

1.2 Milk Pasteurization using Geothermal Brine

Geothermal brine has been utilized for milk pasteurization in various location. Lund (1997) has summarized the use of geothermal brine for milk pasteurization. Medo-Bel Creamery in Klamath Falls, Oregon, was operating the pasteurization unit using geothermal brine, but is no longer in operation. Pumping equipment was used to pump up to 6.3 L/s of geothermal fluid into the HTST pasteurizer (Cherry Burrell plate heat exchanger of stainless steel construction).

Figure 2 shows the simplified process flow diagram for Medo-Bel milk pasteurization. The geothermal water was pumped from the well at 87º C into the building and through a three-section plate heat exchanger. The incoming cold milk at 3ºC was heated by milk coming from the homogenizer in one section of the plate heat exchanger. The milk was then passes to the second section of the plate heat exchanger where the geothermal fluid heated the milk to a minimum temperature of 78ºC for 15 seconds in the short-time pasteurizer. If the milk temperature dropped below 74ºC, the HTST pasteurizer automatically recirculated the milk until the required exposure as obtained. Once the milk was properly pasteurized, it was passed through the homogenizer and then pumped back through the other side of the first section of the plate heat exchanger where it was cooled to 12ºC by the incoming cold milk. It was finally chilled to 3ºC by cold water in the third section of the plate heat exchanger, where the milk went into the cartons with no chance of cook on. This insured both flavor and longer shelf life. As an added bonus, the outgoing heated milk was cooled somewhat by passing it by the incoming cold milk and the cold milk was in turn heated slightly by the outgoing milk. Milk was processed at a rate of 0.84 L/s, and a total of 225,000 kg were processed each month.

Geothermal brine also used for pasteurization in Oradea, Romania. The plant has been in operation since 1981, but it is not known whether the plant is still in operation or not. The milk factory produces 70,000 L/day of milk in the winter and 200,000 L/day of milk in the summer for savings of about $120,000 per years (Lund, 1997). The geothermal fluids is first passed through a series of shell-and-tube heat exchangers which provides secondary water for heating the factory. This secondary water is then passed through plate heat exchangers to pasteurize the milk. The geothermal fluid is also used preheat air to produce milk powder. The milk powder requires 300°C air for drying. The peak geothermal use for all processes is 17 L/s.

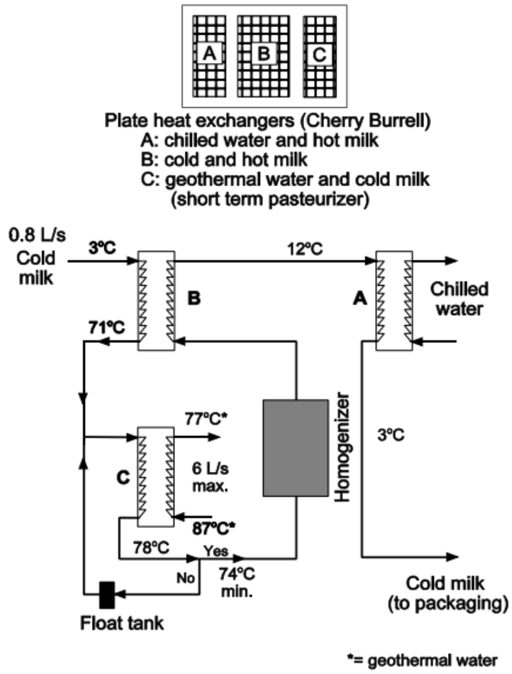

Figure 2: Medo-Bel milk pasteurization flow diagram (Lund, 1997)

Other than existing application, a paper also published to discuss about possible use of geothermal brine for milk pasteurization in Pangalengan, Indonesia. The paper was written by Jubaedah et al. (2015) and consisted of shell and tube heat exchanger design to be used in milk pasteurization. The design uses 18.8 kg/s geothermal brine out of 27.0 kg/s available to generate 1.17 kg/s of hot water at 134°C outlet temperature, but based on calculation, the temperature of hot water will drop to 90°C at the pasteurizer's inlet. This hot water was then used to pasteurize the milk to 72°C. Although it is possible to use the geothermal brine directly for pasteurizer heater, the author chose to utilize hot fresh water as a secondary liquid to mitigate the risk of food poisoning.

Conventional milk pasteurization process usually burn any kind of fuel to heat the hot water. With the use of fuel, the pasteurization process can be thought to have a secure supply of hot water with constant temperature. In other words, the temperature and flow rate of the heating fluid is always consistent. When geothermal brine is used for milk pasteurization, the temperature and flow rate of geothermal brine itself may fluctuate. If the demand for geothermal brine is not large compared to the total geothermal brine flow rate available, then the process could still be secure from any fluctuation since the fluctuation will have very small impact. If the flow rate of geothermal brine available is not as far exceeding the minimum demand for pasteurization process, then the pasteurization process is susceptible to fluctuation of geothermal brine temperature and flow rate. A drop in geothermal brine's temperature or flow rate could reduce the milk outlet temperature in pasteurizer, therefore reducing the quality of the milk itself. Temperature and flow rate reduction of geothermal brine can be caused by many factors such as rain, reservoir or well decline, and well shut-in due to well maintenance or other factors. Unlike conventional pasteurization system, these kind of disturbances can not be overcome by using FDV only because the heat rate available is inherently less than required. The only way to overcome this problem is either by reducing the flow rate of the milk itself (if reduce in capacity is permitted), or by using another alternative heater (using fuel). Reducing the milk flow rate can be done using manually operated valve. However, to achieve a more accurate control of process, an automatic process control system is needed. Automatic process control will also give easier operation since it does not need an operator to manually adjust the valve.

2. TRANSIENT RESPONSE OF HEAT EXCHANGER FOR MILK PASTEURIZATION

A mathematical model is desired to see the response of the heat exchanger outlet stream temperature under fluctuation of various input parameter (disturbance). Various authors have developed mathematical models of the transient response of tubular heat exchanger (double pipe or shell and tube heat exchanger). These models are valid for both double pipe and shell and tube heat exchanger, although there are some assumption that has to be made especially for baffled shell and tube heat exchangers. The baffles in shell and tube heat exchanger causes the shell fluid flow to be crossflow to some degree relative to the tube arrangement. Most of the model that has been developed assume pure counterflow for the shell fluid flow.

The mathematical model was used to simulate the transient response of the milk stream coming out of the heat exchanger when there is a disturbance from steady state condition. A two fluid heat exchangers is in steady state when the inlet and outlet temperatures of the fluid streams are constant over time. As one of the streams experiences a change in its inlet temperature, the heat exchanger undergoes a transient excursion (Bunce et al.). Mathematical model for 1-1 (1 shell pass, 1 tube pass) counterflow heat exchanger has been developed by Shah (1981). This model assumes the following conditions: i) the temperatures of both fluids and the wall depend on time and position from either end of tube bundle, ii) heat transfer between the exchanger and the surroundings is negligible, iii) the mass flow rates of both streams do not vary with time and fluid passages are uniform in cross section giving a uniform fluid inventory in the heat exchanger, iv) the velocity and temperature of each fluid at the inlet are uniform over the flow cross section and are constant with time except for the imposed time step change, v) the convective heat transfer coefficient on each side and the thermal properties of both fluids and the wall are constant, vi) longitudinal heat conduction within the fluids and wall is neglected, vii) the heat transfer surface area on each fluid side is uniformly distributed in the heat exchanger, viii) either the fouling resistances are negligible or they are lumped with the thermal resistance of the wall, ix) the thermal capacitance of the heat exchanger enclosure is considered negligible relative to that of the heat transfer surface.

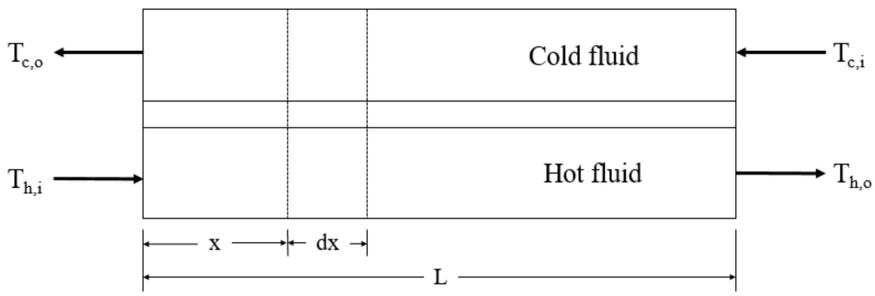

Figure 3: Schematic drawing of heat exchanger and a control volume (Bunce et al., 1995)

The governing differential equations were build based on the scheme described by Figure 3. Applying an energy balance to the incremental control volumes around the hot fluid, the cold fluid, and the wall yields the following differential equations after simplification:

$$\bar{C}_h \frac{\partial T_h}{\partial t} + C_h L \frac{\partial T_h}{\partial x} + (\eta_0 hA)_h (T_h - T_w) = 0 \tag{1}$$

$$\bar{C}_c \frac{\partial T_c}{\partial t} - C_c L \frac{\partial T_c}{\partial x} - (\eta_0 hA)_c (T_w - T_c) = 0 \tag{2}$$

$$\bar{C}_w \frac{\partial T_w}{\partial t} - (\eta_0 hA)_h (T_h - T_w) + (\eta_0 hA)_c (T_w - T_c) = 0 \tag{3}$$

A more simplification could be made if the heat capacities of the tube and shell walls are neglected (assumed to be zero), thereby eliminating Equation (3). Equation (1) and (2) reduces to:

$$\bar{C}_h \frac{\partial T_h}{\partial t} + C_h L \frac{\partial T_h}{\partial x} + (\eta_h hA)_h (T_h - T_c) = 0 \tag{4}$$

$$\bar{C}_c \frac{\partial T_c}{\partial t} - C_c L \frac{\partial T_c}{\partial x} - (\eta_c hA)_c (T_h - T_c) = 0 \tag{5}$$

To simplify the form of the differential Equation (4) and (5), a new variable is defined as follows

$$\varepsilon = \frac{x}{L} \tag{6}$$

With definition as described by Equation (6), the space (length) variable will always have a value between 0 and 1. Applying Equation (6) to Equations (4) and (5) to get:

$$\bar{C}_h \frac{\partial T_h}{\partial t} + C_h \frac{\partial T_h}{\partial \varepsilon} + (\eta_h hA)_h (T_h - T_c) = 0 \tag{7}$$

$$\bar{C}_c \frac{\partial T_c}{\partial t} - C_c \frac{\partial T_c}{\partial \varepsilon} - (\eta_c hA)_c (T_h - T_c) = 0 \tag{8}$$

Initial and boundary conditions are needed to solve the Equations (7) and (8). The initial condition are as follows:

$$T_h(\varepsilon, 0) = f_h(\varepsilon) \tag{9}$$

$$T_c(\varepsilon, t) = f_c(\varepsilon) \tag{10}$$

The initial condition function $f_h(x)$ and $f_c(x)$ can be taken arbitrary as long as it does not create cross temperature within the heat exchanger. After several time step (∂t), the temperature distribution reached steady state and the steady state temperature distribution could be used as the initial condition for the next simulation. For start up, initial condition could taken as follows:

$$T_h(\varepsilon, 0) = T_{h,in} \tag{11}$$

$$T_c(\varepsilon, 0) = T_{c,in} \tag{12}$$

The boundary condition are:

$$T_h(0, t) = T_{h,in} \tag{13}$$

$$T_c(1, t) = T_{c,in} \tag{14}$$

Two more boundary conditions are defined at both outlet stream temperatures.. The problem is the outlet temperature of both stream are a function of time. By applying heat balance on the outlet of each stream (at $\varepsilon = 0$ for hot stream and $\varepsilon = 1$ for cold stream) following equations can be obtained:

$$W_h C_{p,h} \left(\frac{\partial T_h}{\partial \varepsilon}\right)_{(\varepsilon=0,t=t)} = W_c C_{p,c} \left(\frac{\partial T_c}{\partial \varepsilon}\right)_{(\varepsilon=0,t=t)} \tag{15}$$

$$W_h C_{p,h} \left(\frac{\partial T_h}{\partial \varepsilon}\right)_{(\varepsilon=1,t=t)} = W_c C_{p,c} \left(\frac{\partial T_c}{\partial \varepsilon}\right)_{(\varepsilon=1,t=t)} \tag{16}$$

Operating condition is needed to solve the equation completely. The operating condition and heat exchanger parameters at Table 2 are described by Jubaedah et al. (2015) at a milk factory in Pangalengan, Indonesia. Using these data, the equations can be solved to obtain temperature distribution across the tube side and shell side for all time step. SCILAB code has been written to solve the equations. This code is embedded in SCILAB'S XCOS to create simulation environment that capable to simulate transient response under disturbance of one or more input variable, and also to simulate the control scheme that will be used to regulate the milk temperature.

	Tube side	**Shell side**
Fluid	Hot Water	Milk
Inlet temperature, °C	90	60
Outlet temperature, °C	80	72
Heat capacity, kJ/kg	4.20	3.93
Mass flow rate, kg/s	1.00	0.89
U, kW/(m^{2}K)	10.03	3.59
Density, kg/m^3	969	1020
Internal diameter, mm	16	254
Outer diameter, mm	19.05	-
Length, mm	1000	1000
Number of tube	55	-

Table 2: Operating condition and heat exchanger parameters of the proposed heat exchanger design for pasteurization in Pangalengan, Indonesia (Jubaedah et al., 2015)

3. SIMULATION RESULT

3.1 Start-up simulation

For start-up simulation, the temperature across the tube side and shell side has been defined as equal as each side's inlet temperature as follows:

$$T_h(\varepsilon, 0) = 90^{o}\mathrm{C} \tag{17}$$

$$T_c(\varepsilon, t) = 60\,^{o}\mathrm{C} \tag{18}$$

The simulation was ran with 40 space points and 1s time step. The result of the simulation is shown in Figure 4. Temperature at t= 0s across the entire length of tube and shell is 90°C and 60°C respectively. The temperature profile then changes gradually until both streams reach steady state at t = 60s.

3.2 Disturbance simulation

The purpose of disturbance simulation was to simulate the transient response of heat exchanger when there is a change (disturbance) in hot water (tube side) inlet temperature. The simulation uses steady state temperature distribution obtained from start-up simulation as initial condition. Initially, the hot water inlet temperature ($T_{h.in}$) is 90°C. After 10 seconds, $T_{h.in}$ is dropped to a certain temperature. For this simulation, the maximum hot water temperature drop was assumed to be 10°C (90 °C to 80 °C) A step change block was used to simulate such disturbance as shown in Figure 5. The response of milk outlet temperature ($T_{c,in}$) was then plotted against time. **Error!**

Reference source not found. shows the milk outlet temperature response for two hot water inlet temperature decrease. A 10°C decrease (from 90 °C to 80 °C) of hot water inlet temperature will leads to 4°C decrease of milk outlet temperature.

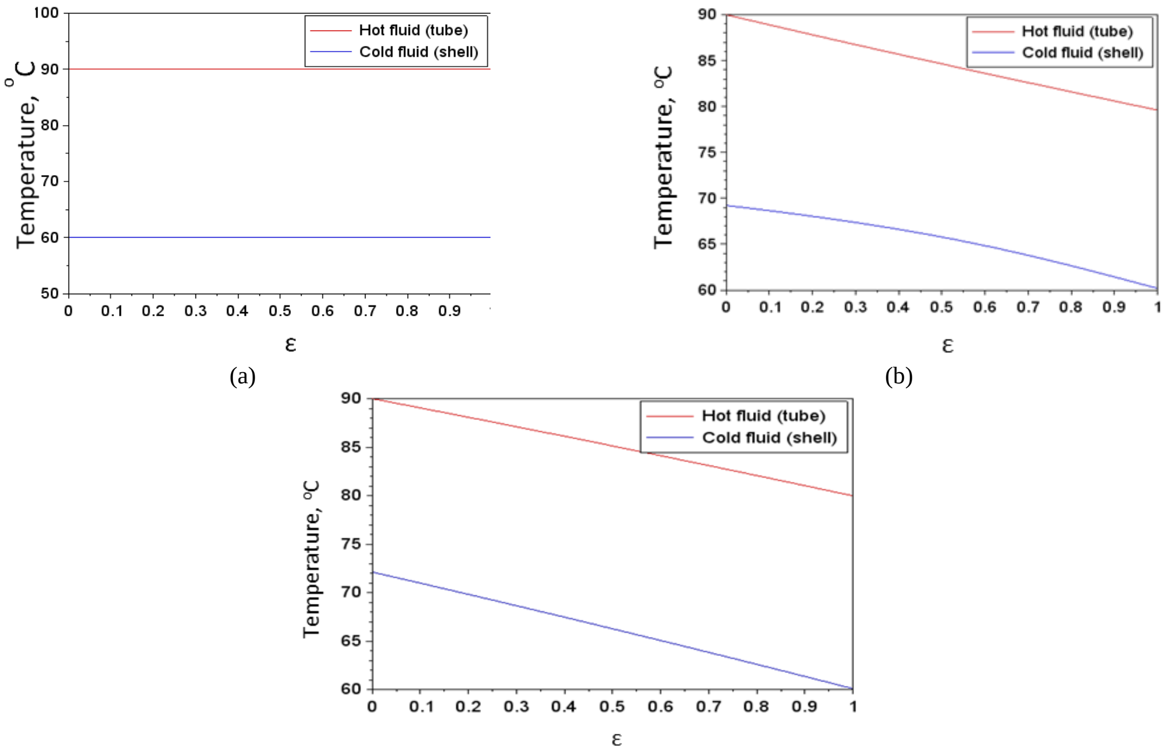

Figure 4: Temperature profile of hot fluid (hot water) and cold fluid (milk) at (a) t = 0 s, (b) t = 30 s, and (c) t = 60 s

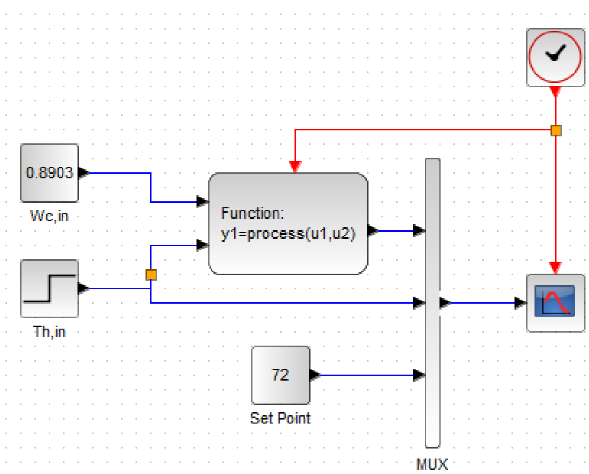

Figure 5: XCOS diagram for disturbance simulation

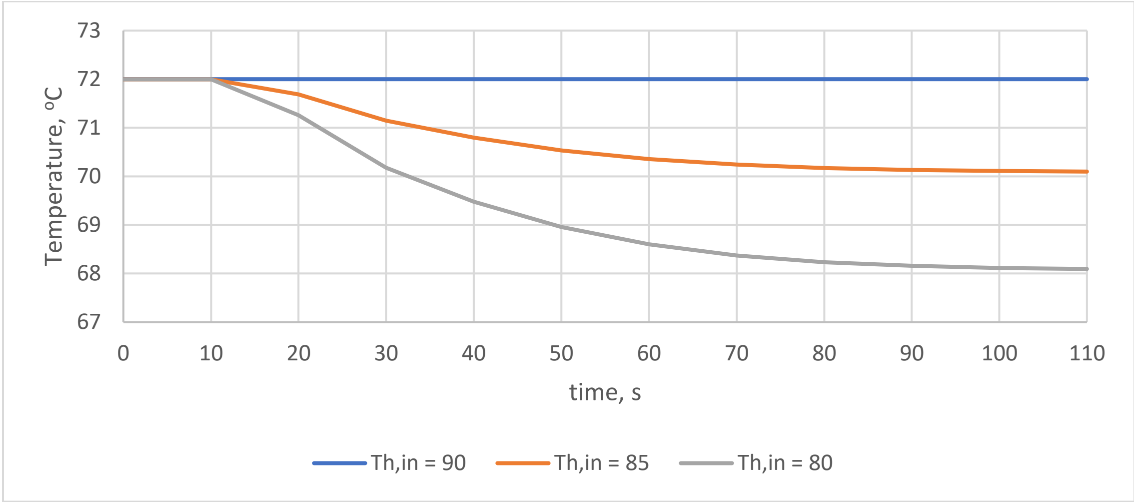

Figure 6: Simulated cold stream outlet temperature ($T_{c,out}$) response with hot stream inlet temperature ($T_{h,in}$) disturbance

3.3 Control Scheme Simulation

To maintain the milk outlet temperature under the effect of hot water inlet temperature reduction, the milk inlet flow rate was regulated. This action compensates the reduction of heat available for milk pasteurization and keeps the milk outlet temperature at desired range. Figure 7 shows a control scheme to regulate the milk flow into the heat exchanger as hot water inlet temperature decrease. Temperature sensor was used to measure the hot water inlet temperature. Measured temperature data was transmitted using electrical signal to proportional controller. Note that the proportional controller uses the error value equals to hot water inlet temperature. The error value is defined as the difference between measured value and the set point value. In this case the set point value for hot water inlet temperature is 90°C. The proportional controller transfer function is described in Equation (19). The K_c value for this proportional controller is 0.036. This value was obtained for from fine tuning the controller, but it is possible to calculate the K_c value by direct mathematical calculation.

$$G_c(s) = K_c \qquad (19)$$

The simulation was run using XCOS with representative diagram as shown in Figure 8. Note that for this simulation, the valve and measuring device's transfer function is neglected, and also the disturbance happened at the exact same time as it detected. This simulation runs with hot water inlet temperature dropped from 90°C to 80°C (-10°C) at t = 5 seconds with no time delay. No time delay means that the control valve reacted at the instance of disturbance detected, so that the milk flow rate was regulated instantaneously. The result could be seen in Figure 9 and it shows that with no time delay, the milk outlet stays constant at 72°C even with 10°C drop of hot water inlet temperature. The simulation was also run with 10 seconds time delay. With 10 seconds time delay, the control valve reacts 10 seconds after the disturbance is detected (or at t = 15 seconds). This time delay value may seemed exaggerated, but it will magnify the effect of delayed control action. The result could be seen in Figure 10 and Figure 11. Figure 11 shows the control system reduce the milk flow rate to 0.53 kg/s to compensate the hot water inlet temperature disturbance. Figure 10 shows that the milk outlet temperature dropped to around 71°C until it finally returned to permittable temperature range at t = 65 seconds. It means that 60 seconds is required from the time disturbance happened until the milk outlet temperature return to normal operation range ($\pm$0.5°C) for 5 seconds time delay. For time delay less than 5 seconds, the milk outlet temperature may be maintained closer, or even within the permittable range.

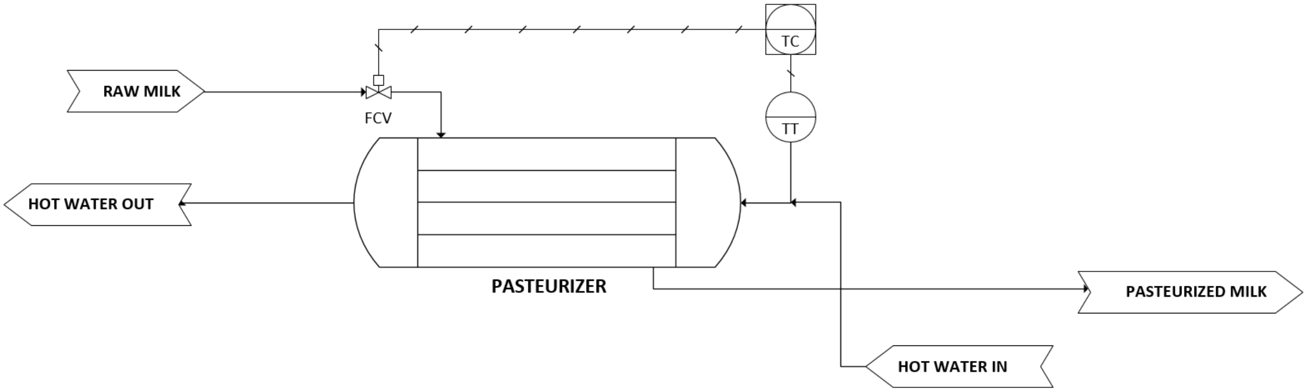

Figure 7: Control scheme using proportional controller

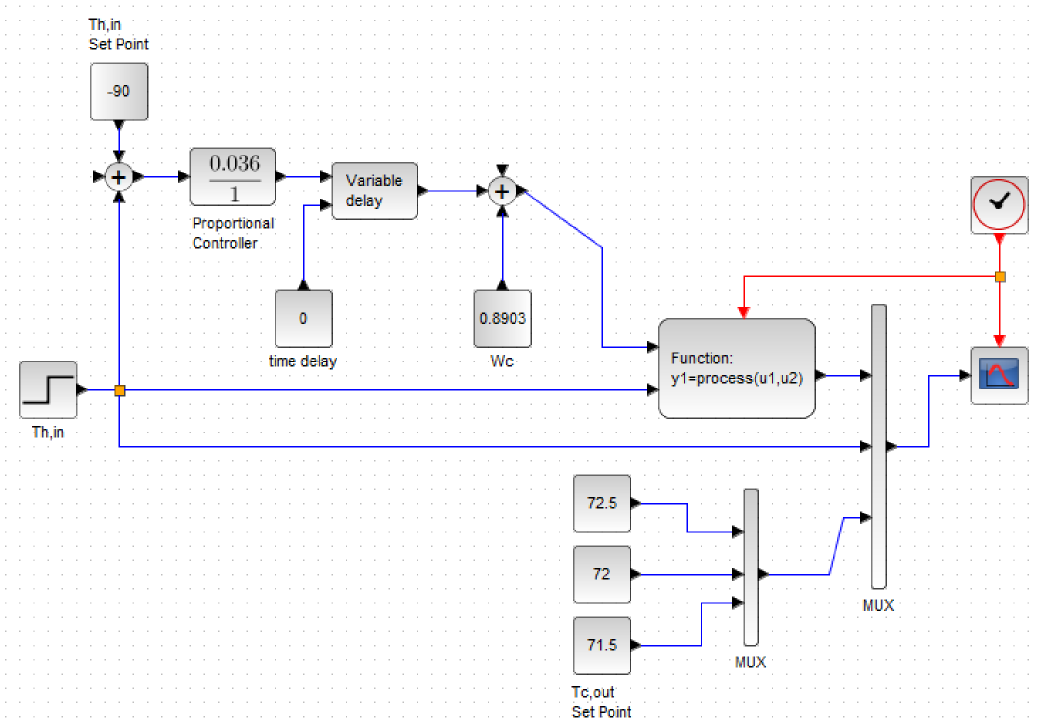

Figure 8: XCOS representative diagram for Figure 7 control scheme

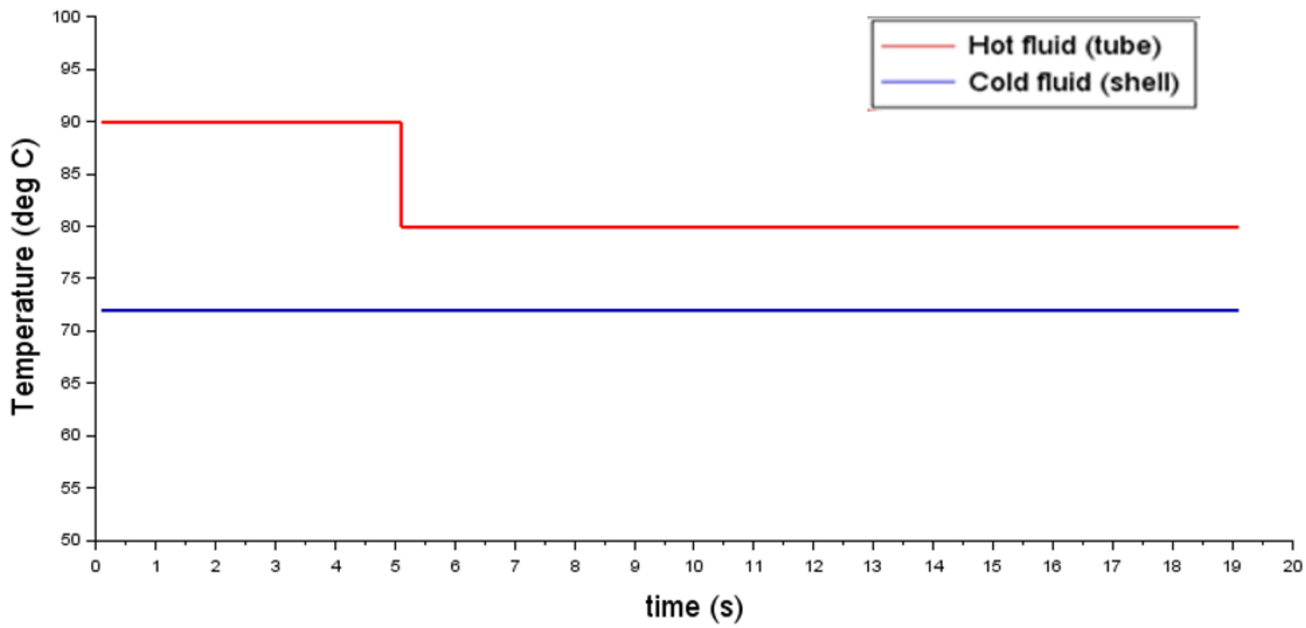

Figure 9: Result of control scheme simulation with -10°C hot water inlet temperature decrease and a proportional controller

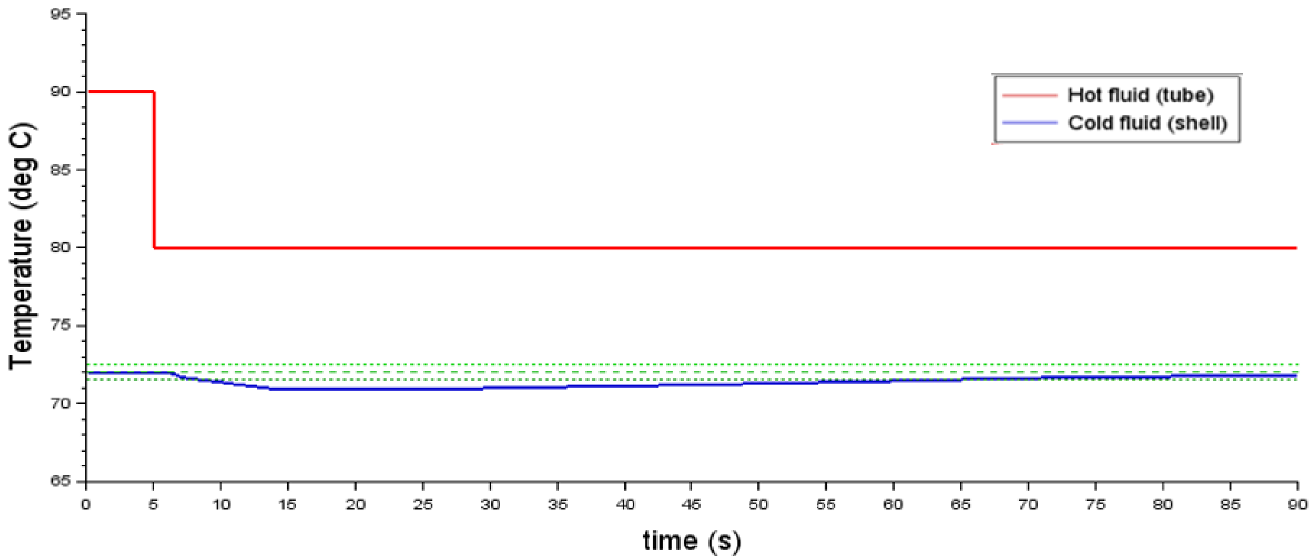

Figure 10: Results of control scheme simulation with -10ºC hot water inlet temperature decrease and a proportional controller, with 10 seconds time delay for the control action

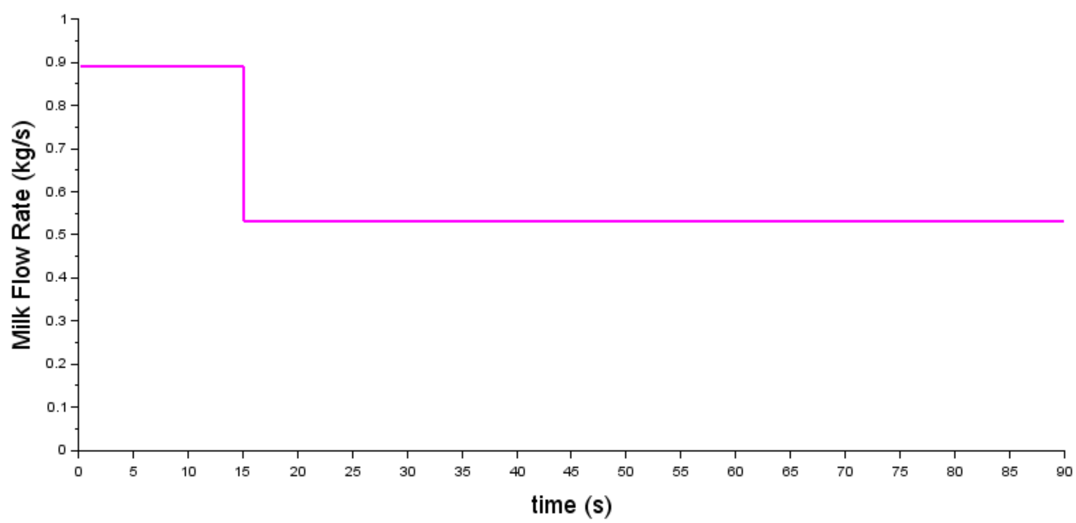

Figure 11: Milk flowrate control response in control scheme simulation with -10ºC hot water inlet temperature decrease and a proportional controller, with 10 seconds time delay for the control action

DISCUSSION

The mathematical model used in this simulation was able to represent the temperature changes as function of time and position. The simplification made to the mathematical model might results in difference between actual and simulated temperature, but the simulation result still shows a reasonable trend of temperature changes over time for both hot and cold stream.

The reduction in hot water inlet temperature clearly affect the milk outlet temperature. Although $\pm$0.5ºC temperature change is permittable for pasteurization process, a deviation more than tolerable temperature range might result in bad quality of milk product. Proportional controller was used to maintain the milk outlet temperature inside the permittable range. By controlling the milk flow rate into the heat exchanger, the controller manage to balance the shortage of heat available due to reduction in hot water inlet temperature. This control system is not meant to be used alone since it only compensate the reduction of hot water inlet temperature which caused by the reduction of geothermal brine flow rate or temperature, or both. This control system might be used with FDV control system to maintain the quality of pasteurization process. Although proportional controller is capable to compensate the reduction of hot water inlet temperature, it might also give a very slow response. A better response could be achieved by utilizing feedback control system. A feedback control system using PID controller might be used to smoothen the output response using temperature sensor positioned at the outlet of the milk stream.

CONCLUSION

The result shows that an automatic proportional control is adequate for milk pasteurization process using geothermal brine with shell and tube heat exchanger. This automatic control may aid and provide ease of operation for milk pasteurization using geothermal brine if the brine supply is not secure. The use of feedback controller to reduce the effect of disturbance even further is also possible, but a more thorough study is needed to ensure that the control system is working properly and doesn't interfere each other. A more thorough mathematical model is also needed for a better simulation accuracy. For example, heat transfer through tube wall should be taken into account to obtain a more accurate result. Overall, the proportional control system coupled with FDV is reliable, yet simple enough to be implemented in pasteurization process using geothermal brine.

NOMENCLATURE

W Mass flow rate

C_p Heat capacity

M Mass of fluid or wall material in heat exchanger

$\bar{C}$ Heat capacitance = MC_p

C Heat capacity rate = WC_p

T Temperature

t Time

L Length

x Distance

h Heat transfer coefficient

A Heat transfer area

η_0 Fin efficiency

Kc Proportional controller coefficient

Subscript

h Hot fluid

c Cold fluid

w Heat exchanger wall

in inlet

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