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Optimization of Design Heat Exchanger to Reduce Fouling Resistance in Milk Pasteurization

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Abstract. Milk pasteurization process used Heat Exchanger (HE) to heat fresh milk at certain temperature and time period. Fouling in heat exchanger during milk pasteurization has been identified as a major problem in the efficiency of energy. Due to insufficient temperature during process, foodborne pathogens may not be killed properly and contaminate the food which make the human health adverse. Other problems may arise in fouling which is losing the efficiency during operation, increasing cost of pumping and downtime that affecting the efficiency of production cost. The fouling resistance depends on milk properties, heat exchanger design technologies and actual operating conditions. The objective of this research was to optimize the heat exchanger design of milk pasteurization by considering series-parallel connection to minimize fouling. The research method was using recent stochastic algorithms Duelist Algorithm, Killer-Whale Algorithm and Rain-Water Algorithm for fouling mitigation in milk pasteurization. The optimization results show the series-series connection reduce fouling up to 16% at the tube side (Rft) and reduce up to 5% at shell side.

1. Introduction

In the food industries, varieties of heat treatments such as milk pasteurization are performed. In milk in pasteurization process, milk is heated and changed the milk stabilities. A milk solids deposit is formed at both of heat-exchanger surface. Even the deposit does not affect to the milk decomposition significantly, it affected to the thermal and hydraulic impact which cause the increasing of operation cost and maintenance cost. Thus, fouling is considered as the worst problem in dairy processing plants. In the crude refineries, heat exchanger network required annual cleaning. In the dairy industries, the best practice of clean interval is every 5-10 hours. The operating cost in the U.S. pasteurized milk industries due to fouling has been approximation in \$140 million annually [1]. However, these were not included the sterilized milk.

The root causes of milk fouling forming have been studied by several studies. The deposit composition has been analyzed. Furthermore, the chemical changes during milk heating have been clearly known which was caused by the presence of proteins and β -lactoglobulin. Lalande *et al.* [2] revealed that heat denaturation of the protein could promote the milk deposit forming. De Jong *et al.* [3] used β -lactoglobulin kinetics reaction to study the fouling deposition that was occurred in plate



heat exchangers. The result of those study described that the deposit had close correlation with reaction rates of protein.

The study concerning on chemical reactions fouling was reported by Paterson and Fryer [4]. The study reported that the milk fouling was classified as chemical reaction fouling with high rate reaction rate. Therefore, the rate of fouling forming in milk pasteurization depended on the fouling reaction. Belmar-Beiny *et al.* investigated the fluid temperature and velocity effects to the fouling whey protein [5]. This study shows the increasing fouling rate was occurred when the milk was heating up in heat exchanger. Two possible fouling type mechanisms are depending on mass and energy transfers and reaction.

Fouling mitigation techniques commonly performed by designing higher efficiency of heat exchanger and applies cleaning scheduling of heat exchanger periodically. In cleaning scheduling of heat exchanger, the loss due to fouling can be avoided [6,7,8]. However, the frequency should be optimized to obtain highest saving. Alternatively, design of new heat exchanger or retrofit existing heat exchanger with larger heat transfer area and higher efficiency can also effective way to performed. Nevertheless, the capital cost of the HEN will be increase [6,9,10].

Design heat exchanger can be performed at internal geometries of heat exchanger and/or at parallel series of heat exchanger connection. The objective of this research was to optimize the design of milk pasteurization process by considering series-parallel connection to minimize fouling. The class of optimization problem was Mixed Integer Non Linear Programming (MINLP). The effective and common algorithm of optimization to solve class of MINLP is algorithm of multi-variable stochastic optimization [11]. Recently, this algorithm consists of the new algorithms, namely Duelist Algorithm [12], Killer-Whale Algorithm [13] and Rain-Water Algorithm [14] due to the effectively achievement of global optimum solution.

2. Literature Review

2.1 Series-parallel connections of heat exchangers

Connection of series-parallel HE affects to mass flowrate and inlet-outlet temperature different. The different of temperature and mass flowrate in the heat exchangers will affect to rate of fouling [2]. Series and parallel connection of heat exchanger can be identified based on the outlet and inlet of heat exchanger. The series connection will affect to temperature difference reducing and it may be decrease the fouling rate as show in figure 1. The parallel connection is usually used to increase production capacity as shown in figure 2.



Figure 1. Series connection of heat exchangers

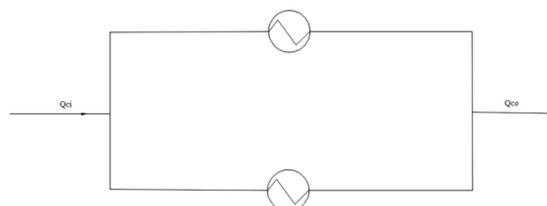


Figure 2. Parallel connection of heat exchangers

2.2 Model of Heat Exchanger

Heat exchanger modeling is used to determine tube and side heat transfer coefficients, overall heat transfer coefficient, heat duty and pressure drops.

2.2.1 Heat Transfer Calculation in Shell Side The method used to calculate heat transfer coefficient in shell side is Bell-Delaware's Method. Shell side crossflow area (S_m) is given by equation 1.

$$S_m = L_{bc} \left[L_{bb} + \frac{D_{ctl}}{L_{tp,eff}} (L_{tp} - d_o) \right] \quad (1)$$

Where : S_m = Shell side crossflow area (m^2); L_{bc} = Central baffle spacing (m); L_{bb} = Bundle to shell clearance (m); D_{ctl} = Bundle diameter (m); $L_{tp,eff}$ = Effective tube pitch (m); L_{tp} = Tube pitch (m); d_o = Tube outside diameter (m);

Shell side mass velocity (G_s) and Reynold number (Re_s) is given by equation 2 and equation 3.

$$G_s = \frac{m_s}{S_m} \quad (2)$$

$$Re_s = \frac{G_s d_o}{\mu_s} \quad (3)$$

Where : G_s = Shell side mass velocity ($kg/s m^2$); m_s = Shell side mass flow rate (kg/s); Re_s = Shell side Reynold number; μ_s = Shell side fluid viscosity ($kg/m s$).

The shell side Prandtl number (Pr_s) is given by equation 4.

$$Pr_s = \frac{\mu_s C_{ps}}{k_s} \quad (4)$$

Where : Pr_s = Prandtl number; C_{ps} = Shell side specific heat ($J/kg ^\circ C$); k_s = Shell side thermal conductivity ($W/m ^\circ C$); μ_s = Shell side fluid viscosity ($kg/m s$)

Ideal heat transfer coefficient (h_i) is given by equation 5.

$$h_i = \frac{j_i C_{ps} G_s (\phi_s)^n}{Pr_s^{\frac{2}{3}}} \quad (5)$$

The term j_i is the ideal Colburn as equation 6, 7 and 8.

$$j_i = 1,73 Re_s^{-0,694} \text{ when } 1 \leq Re_s \leq 100 \quad (6)$$

$$j_i = 0,717 Re_s^{-0,574} \text{ when } 100 \leq Re_s \leq 1000 \quad (7)$$

$$j_i = 0,236 Re_s^{0,346} \text{ when } 1000 \leq Re_s \quad (8)$$

The term (ϕ_s) is viscosity correction factor, which accounts for the viscosity gradient at the tube wall (μ_w) versus the viscosity at the bulk mean temperature (μ_s) of the fluid as equation 9.

$$(\phi_s)^n = \left(\frac{\mu_s}{\mu_{sw}} \right)^{0,14} \quad (9)$$

Where, h_i = Ideal heat transfer coefficient ($W/ m^2 \text{ } ^\circ C$); j_i = Ideal Colburn; μ_{sw} = Viscosity at bulk mean temperature ($kg/m \text{ } s$);

Shell side heat transfer coefficient is given by equation 10

$$h_s = h_i J_c J_l J_b J_s J_r \quad (10)$$

Where, h_s = Shell side heat transfer coefficient ($W/ m^2 \text{ } ^\circ C$); h_i = Ideal heat transfer coefficient ($W/m^2 \text{ } ^\circ C$); J_c = Segmental baffle window correction factor; J_l = Correction factors for baffle leakage effects for heat transfer; J_b = Correction factors for bundle bypass effects for heat transfer; J_s = Correction for unequal baffle spacing at inlet and/or outlet ; J_r = Correction factor for adverse temperature gradient in laminar flow

2.2.2 Heat Transfer Calculation in Tube Side The method used to calculate heat transfer coefficient in tube side is Bell-Delaware's Method. Tube side flow area is given by equation 11.

$$A_t = \frac{\pi d_i^2 N_t}{4} \quad (11)$$

Tube inside diameter is given by equation 12.

$$d_i = d_o - 2 t_w \quad (12)$$

Number of tube is given by equation 13.

$$N_t = \frac{0,78 d_{ctl}^2}{L_{tp}^2} \quad (13)$$

Where : A_t = Tube side flow area (m^2); d_i = Tube inside diameter (m); d_o = Tube outside diameter (m); N_t = Number of tube; t_w = Tube thickness (m); D_{ctl} = Bundle diameter (m); L_{tp} = Tube pitch (m)

Tube side mass velocity (G_t) is given by equation 14.

$$G_t = \frac{m_t N_p}{A_t} \quad (14)$$

Where, G_t = Tube side mass velocity ($kg/ s \text{ } m^2$); m_t = Tube side mass flow rate (kg/s); N_p = Number of tube pass

Reynold number is given by equation 15.

$$Re_t = \frac{G_t d_i}{\mu_t} \quad (15)$$

Where, Re_t = Tube side Reynold number; μ_t = Tube side fluid viscosity ($kg/m \text{ } s$)

Prandtl number is given by equation 16.

$$Pr_t = \frac{C_{p_t} \mu_t}{K_t} \quad (16)$$

Where, C_{p_t} = Tube side specific heat (J/kg °C); K_t = Tube side thermal conductivity (W/ m °C)

Tube side heat transfer coefficient is calculated by CollBurn equation as equation 17.

$$h_t = 0,023 Re_t^{0,8} Pr_t^{0,4} \left(\frac{K_t}{d_i}\right) \left(\frac{\mu_t}{\mu_w}\right)^{0,14} \quad (17)$$

Where, h_t = Tube side heat transfer coefficient (W/m² °C)

2.2.3 Calculation of Overall Heat Transfer Coefficient Heat transfer rate is affected by overall heat transfer coefficient, area of heat transfer, and logarithmic mean temperature difference as show in equation 18-21.

$$cond = \frac{d_o \left(\ln\left(\frac{d_o}{d_i}\right)\right)}{2 K_{cs}} \quad (18)$$

$$\frac{1}{U_f} = \frac{d_o}{d_i h_t} + \frac{d_o R_{ft}}{d_i} + cond + R_{fs} + \frac{1}{h_s} \quad (19)$$

Where, U_f = Overall heat transfer coefficient under fouling conditions (W/m² °C); $Cond$ = Conduction heat transfer (m² °C /W); K_{cs} = Thermal conductivity of tube material (W/ m °C); R_{fs} = Shell side fouling resistance (m² °C /W); R_{ft} = Tube side fouling resistance (m² °C /W)

Heat duty is given by equation 20.

$$Q = U_f LMTD_{corr.} A_o \quad (20)$$

Where, U_f = Overall heat transfer coefficient under fouling conditions (W/m² °C); $LMTD_{corr.}$ = Log Mean Temperature Difference corrected (°C); A_o = Area of heat transfer (m²)

Log Mean Temperature Difference corrected ($LMTD_{corr.}$) is given by equation 21.

$$LMTD_{corr.} = LMTD . F \quad (21)$$

Where, $LMTD$ = Log Mean Temperature Difference (°C); F = Correction factor

$LMTD$ is the average temperature difference between hot and cold fluid. $LMTD$ is calculated by the equation 22.

$$LMTD = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln\left(\frac{T_{h,i} - T_{c,o}}{T_{h,o} - T_{c,i}}\right)} \quad (22)$$

Area of heat transfer is given by equation 23.

$$A_o = \frac{22}{7} d_o L_{ti} N_t N_s \quad (23)$$

2.2.4 *Calculation of Pressure Drop* Pressure drop in tube side utilize Pethukov and Popov's Methods as equation 24 and 25.

$$\Delta P_t = \left[2 \times f \frac{L \times N_p}{d_i} + 2 \times N_p \right] \times \rho_t \times V^2 \quad (24)$$

$$f = (1,58 \ln Re_t - 3,28)^2 \quad (25)$$

Where : ΔP_t = Tube side pressure drop (kg/cm²); f = Friction factor; L = Tube length (m); ρ_t = Tube side fluid density (kg/m³); V = Fluid velocity (m/s)

Pressure drop in shell side utilizing Bell Delaware's Methods as equation 26 and 27.

$$\Delta P_s = \frac{2 f G_s^2 D_s (N_b + 1)}{\rho_s d_o \left(\frac{\mu_s}{\mu_w} \right)^{0,14}} \quad (26)$$

$$f = e^{0,576 - 0,19 \ln Re_s} \quad (27)$$

Where : ΔP_s = Shell side pressure drop (kg/cm²); f = Friction factor; ρ_s = Shell side fluid density (kg/m³)

2.2.5 *Calculation of Fouling Resistance* Calculation of fouling resistance utilize Fryer and Slater model [2] as equation 28.

$$\frac{dRf}{dt} = \left[\frac{4.85}{Re} \times 10^{13} \exp\left(\frac{-87 \times 10^5}{RT}\right) \right] \times \left[\frac{1}{U_o} \right] \quad (28)$$

3. Recent Stochastic Algorithms

3.1 Duelist Algorithm

Biyanto [12] has developed Duelist Algorithm (DA) which was inspired by the capabilities being the winner, loser and champion in duelist. These included an evolutionary computation technique which was tested by a total of 11 different optimization problems and showed to be more robust than other recent stochastic algorithms.

3.2 Killer-Whale Algorithm (KWA)

Biyanto [13] has built KWA which was inspired by the life of Killer Whale during hunting the prey and has been compared with others algorithm, such as GA, CMA-ES, SA and ICA. This was tested by a total of 6 objective functions with . cauchy noise, gaussian noise, and uniform noise.

3.3 Rain-Water Algorithm (RWA)

Biyanto [14] has built RWA which was based on the pattern of free fall rain water that were from atmosphere to the lowest earth surfaces. RWA was found to be capable in providing the better performances compare to other four algorithms specifically on the speed of convergent [14].

4. Research Method

In general, the flow chart of research methodology of series-parallel heat exchanger design using recent stochastic algorithms for fouling mitigation in milk pasteurization was shown in figure 3.

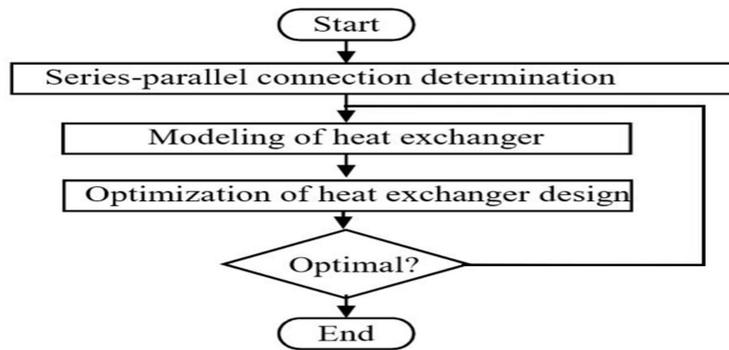


Figure 3. Optimization of heat exchanger design flow chart

5. Results and Discussions

Since series-series connection of heat exchanger provided lowest fouling resistance, the rest discussions only focus on series-series connection. In this research, modeling of series-parallel heat exchanger have been developed and optimization of heat of heat exchanger design for milk pasteurization have been performed using recent stochastic optimization algorithms.

In present study, KW, DA, and RWA were applied to optimize fouling resistance in milk pasteurization design. The optimized variables are shell inside diameter (D_s), tube outside diameter (d_o), and the number of baffles (N_b). The objective function during iterations can be seen in the results below. These algorithms exhibited similar optimization results. However, the time to reach optimum value are varies due to code and parameters for each algorithm as shown in figure 4.

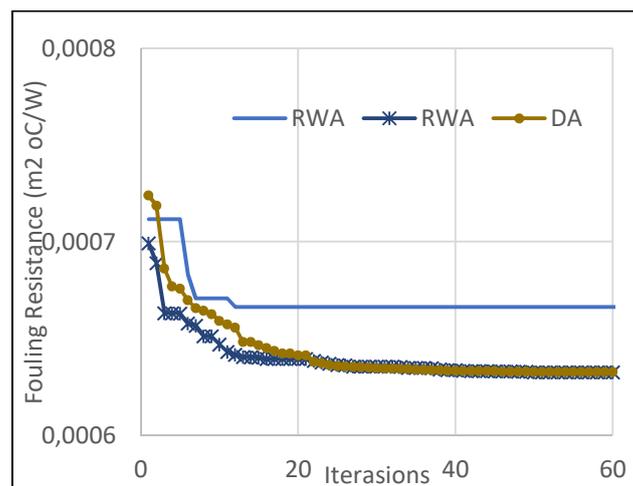


Figure 4. The minimized objective function of fouling resistance during iterations.

These results show that DA, KWA and RWA can optimize fouling resistance in milk pasteurization design due to their robustness. Biyanto [12, 13, 14] revealed that DA, KWA and RWA was more robust compared to other algorithms. The difference between them is speed to achieve global optimum.

Table 1. The Effect of Series-Series Heat Exchangers

Variables	Unit	Design	Optimization	Difference
Uf	w/m ² °C	342.55	364.84	7%
Ao	m ²	101.67	96.96	-5%
Ps	psi	04.59	04.28	-7%
Pt	psi	04.58	04.43	-3%
Rft	m ² °C / W	0.00048 72	0.0004622	-5%
Rfs	m ² °C / W	0.00008 64	0.0000722	-16%

Detail optimization results are tabulated in table 1. The table 1 shows fouling resistance at tube and shell side after optimization reduce 16% and 5%, respectively. It performances were obtained due to optimization in the proper selection of tube side outside diameter, shell side diameter and number of baffle. Moreover, the size of heat exchanger reduces 5% and differential pressure reduces up to 7%. The size of heat exchanger reducing will reduce capital cost. The reducing of differential pressure will reduce the price of pump and reduce the operational cost of pumping fluids.

6. Conclusions

By using DA, KWA and RWA for the optimization of fouling resistance in milk pasteurization, the series-series connection reduce fouling up to 16% at the tube side and up to 5% at shell side.

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