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Assessment of Plate Heat Exchanger Optimization in Soybean Milk Processing

[1]Abd El-Salam, M. F. Moustafa, [2]Manal, A. Sorour, [1]Anwar, A. Ashraf & [2]*Omnia, E Salama

[1]Agricultural Engineering Department, Faculty of Agriculture, Ain Shams University, Cairo, Egypt
[2]Food Engineering and Packaging Department, Food Technology Research Institute, Agricultural Research Center, Giza, Egypt.

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ABSTRACT

The most crucial factors to consider when creating soybean milk, a device for transferring heat between two fluids, are the heating conditions. The field of thermal engineering is particularly active when it comes to heat exchanger design optimization. Using performance data on the use of cooling soybean milk with chilled water, an optimum channel flow velocity and an ideal number of plates were determined. To determine the optimum channel flow velocity and plate count, performance data on the use of cooling soybean milk with cold water were used. Using a Brookfield rheometer, the apparent viscosity of soybean milk was determined on both the hot and cold sides. Additionally, the annual cost, purchase cost, and fixed cost were calculated. Pressure drops and Reynolds numbers for fluids were computed. For an annual production rate of 43797.65 m^3/year, it was discovered that the minimum flow velocity is 2.25 m/s, the ideal number of plates is 17, and the minimal total yearly cost is 35000 L.E./year.

1. Introduction

Nowadays, because of its nutritional benefits, soymilk is one of the most consumed beverages. It is a traditional beverage from East Asia made from plants. Its high protein content is the primary factor in its appeal. In this study, soymilk was made, and a variety of tools were used to analyze its qualities. (Ayushi et al., 2018). Soy milk is a low-cost, remarkably adaptable, high-protein beverage manufactured from soybeans. It is a seed-based, white liquid. In contrast to most other protein-rich foods, milk is free of cholesterol and low in fat, especially saturated fats. The protein quality is on par with that of chicken. Because it has fewer calories, it is also helpful for dieters. Given that it has vegetable protein, which is both very nourishing and easily digestible, it is a great food for infants, children, the elderly, pregnant women, and nursing mothers. Tofu (soya paneer), a derivative of soy milk, is the least expensive form of protein. It is used to make delectable entrees like matar paneer and palak paneer as well as snacks like soya burgers, patties, sandwiches, pakoras, and other foods, as well as desserts. It can be supplemented with calcium, vitamins A, B-12, and D, and is a reliable source of potassium. Although it has less calories than whole milk and around the same number of calories as 1% or 2% percent milk, it has the same amount of protein as cow's milk. Little saturated fat is present. (Matej et al., 2022). Because of microbial activity, soy milk has a relatively short shelf life, which is one of its main drawbacks. The issue of short life can only be resolved by combining several preservation strategies. Soymilk can be preserved using a variety of methods, including heating, high pressure processing, pulsed electric fields, ohmic heating, and drying.

***Corresponding Author**
Email: omniasalama31@gmail.com

In comparison to storage at ambient temperature, all these preservation techniques perform better when kept in a refrigerator. Deepika Kohli, among others, generally comprises between 8 and 10 percent of total solids, 3.6% of protein, 2.0% of fat, 2.9% of carbs, and 0.5% of ash (Sorour et al., 2014)

The heating conditions are the most important considerations while making soymilk. The solids and protein yield and nutritional quality of soymilk, as well as its color and flavor, are principally affected by the heat treatments applied during extraction, cooking, and subsequent pasteurization or sterilization. (KinChor and Keshavan, 2007). An apparatus for exchanging heat between two fluids of different temperatures is a heat exchanger (HX). (Bhuiyan and Islam, 2011)

Higher-temperature fluids transmit heat to lower-temperature fluids. Heat transfer occurs from a higher-temperature fluid to a lower-temperature fluid. In most heat-related devices, the heat transfer surface separates two fluids, which may vary with several types of heat exchangers. The many forms of construction, flow configurations, compactness of the surface, transfer method, pass configuration, fluid phase, and heat transfer mechanism are used to categorize heat exchangers. Heat exchangers can be parallel flow, counter flow, cross flow, cross-counter flow, etc. depending on the flow configuration (Bergman and Incropera, 2011).

Equipment that converts heat from a hot fluid to a cool fluid is called a heat exchanger. The temperature of the fluid varies as it travels the length of the heat exchanger while it is being heated. Heat is recovered between two process streams by use of heat exchangers. Heat exchangers are widely used in space, refrigeration, and air conditioning systems, as well as power plants (Srinivasa Rao et al., 2014)

Heat exchangers have a wide range of uses, according to (Pouya Jamzad et al., 2019), including the oil and gas industry, food and chemical processing, power production, refrigeration, and air conditioning systems. Developments in chemical, petrochemical, and HVAC systems have resulted in an ever-increasing market requirement for efficient and compact heat exchangers due to rapid industrialization and a growth in energy needs. Plate heat exchangers are regarded as compact among the several types of heat exchangers because they offer a large surface area for heat transmission per volume. The thin plate in plate heat exchangers moves heat from the hot to the cold streams. The usage of plate heat exchangers (PHEs) is widespread in a number of sectors, including energy generation, food processing, chemical, refrigeration and air conditioning, and marine. PHEs are now utilized in high-pressure applications due to recent advancements in plate design, sealing, and other mechanical integrity elements. Due to their lower volume-to-surface area ratio, PHEs are categorized as compact devices. (Ayub, et al., 2019)

A PHE typically comprises of numerous corrugated or embossed metal plates near one another. Each plate includes four sealable apertures that act as alternate flow channels for the fluids' intake and outflow ports. They are widely utilized for many industrial applications due to their compactness, efficiency, design flexibility, and low cost. Adjacent plates create the flow passageways that allow the two streams to exchange heat while traveling down different channels. Figure 1. (Zhang et al., 2019) illustrates this.

Depending on the needs of the application and the specific use case, performance optimization and performance improvement of these components can be pursued by evaluating a variety of different metrics. These include component material reduction, size reduction, manufacturing cost reduction, reduction of pumping power, or some combination of these objectives. While some of these metrics are conceptually simple (e.g., cost and size reduction), the heat capacitance according to (Nikolaos et al., 2018). The goal of the article is to identify the ideal plate number, velocity, and total annual cost for a plate heat exchanger utilized in the production of soybean milk (Sorour et al., 2009).

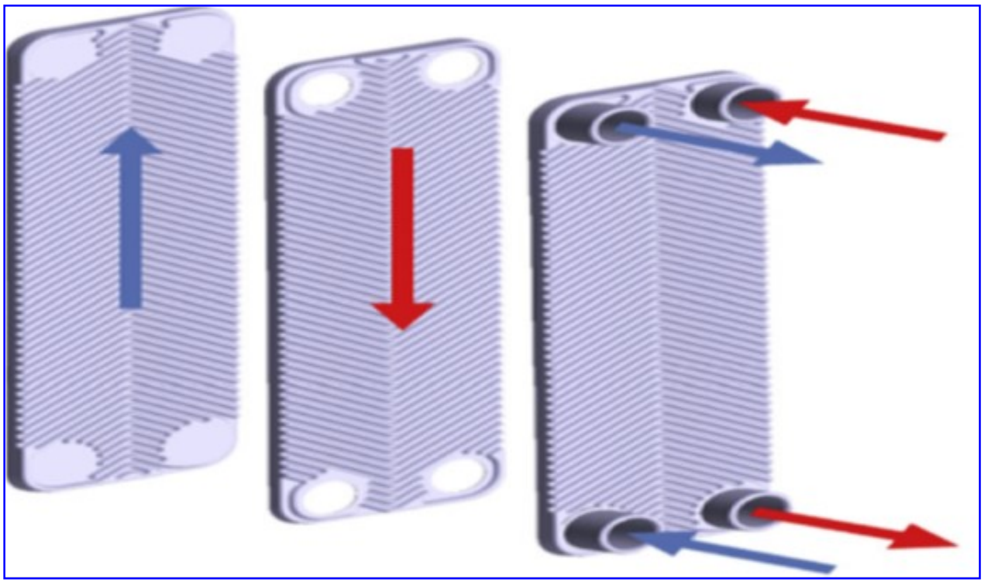

Figure 1. A diagram of hot and cold fluid flows in alternate passages in PHE (Sarraf, et al., 2015)

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2. Materials and Methods

Soybean Milk Processing

The Agricultural Research Center's Food Technology Institute produced soymilk using the following process. Nowadays, soymilk is one of the most consumed beverages because of its nutritional benefits. It is an East Asian beverage made from plants. Its high protein content is the primary factor in its appeal. In this work, soymilk was produced, and its characteristics were examined using a variety of tools (Ayushi, et al., 2018)

To get rid of stones and broken, deformed seeds, soybeans were sorted and cleaned. After washing, the dried soybean was submerged for 12 hours in 500g of water in 1 Litre of water. After that, it was rinsed and blanched for 30 minutes in 1.25% NaHCO3. The dried soybean was then rinsed, washed again, and then manually dehulled. To eliminate the okra, the soybean seeds were blended and expressed in a 3:1 (water to beans on a weight basis) ratio. After that, preservatives and antioxidants are added to the milk to make it more palatable. The milk was then pasteurized for 15 seconds at 71 ^{o}C. (Deepika Kohli, et al., 2017)

Boiling and homogenization are the two phases of pasteurization. Pure soy milk that has been boiled in a double-jacketed tank with saturated steam is the substance that has been filtered. The milk is kept out until it reaches a temperature of 90 to 100^{o}C. During this stage, non-volatile additives including coco, fat "corpulence", aliment reagents, and stabilizers are introduced. This procedure not only eliminates the volatile off-flavors but also renders inactive any enzymes that have not yet been rendered inactive and may have contributed to the development of off-flavor during storage. Soybean milk at temperature 90 – 100ºC from the boiling stage is then pumped to the two-stage homogenizer; the homogenizer breaks molecules down to form a homogeneous mixture so that the liquid materials can be blended more evenly.

The homogenous soy milk is placed in a plate heat exchanger, which typically has between 9 and 11 plates, and is cooled to 4°C from its initial temperature of about 90°C. Soybean milk is cooled using chilled water at 1°C. The flow counter for hot and cold fluids is on right now. The storage tank for soybean milk is then kept at 4°C. At this point, volatile chemicals such flavors like "vanilla" should be applied before packaging. (Sorour, et al., 2014)

Soymilk Viscosity

Shear rate, shear stress, and viscosity of soymilk and sugary beverages were determined using a Brookfield rotational viscometer model HA DVIII Ultra (Brookfield Engineering Laboratories, Inc.). The temperature was maintained using a thermostatically controlled water bath. (Alpaslan and Hayta, 2007).

Stepwise Procedure for Calculation:

The basic equations of heat transfer are used and explained below to appreciate the data taken from experiments:

The heat exchange rate Q was evaluated for the hot and cold sides of the plate heat exchanger (Cabral et al., 2010).

$$Q = m_h\, C_{p,\,h}\, (Th_{,\,in} - T_{h,\,out}) \qquad (1)$$

$$Q = m_c\, C_{p,\,c}\, (Tc_{,\,out} - T_{c,\,in}) \qquad (2)$$

The fluid properties (ρ, μ, Cp) are evaluated at bulk temperatures, which are calculated as (Kakaç and Liu, 2002; Srinivasa Rao et al., 2014).

$$T_{c,b} = \frac{(Tc,in\ + Tc,out)}{2} \qquad (3)$$

$$T_{h,b} = \frac{(T_{h,in} + T_{h,out})}{2} \qquad (4)$$

To find the overall heat transfer coefficient, total surface area and log-mean temperature must be known, where log-mean temperature is calculated as:

$$\Delta T_m = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln(T_{h,in} - T_{c,out})/(T_{h,out} - T_{c,in})} \qquad (5)$$

The actual heat transfer rate Q can be determined by:

$$Q = U_D\, A\, \Delta T_m \qquad (6)$$

The effective heat transfer area in a PHE, A, is calculated by multiplying the total number of plates in the exchanger minus two by the effective area per plate (Sorour et al., 2014)

A = (No. plates - 2) ×area per plate (7)

(Kern, 1965) said Reynolds number can be considered to characterize the flow dominantly, which is found by mass velocity, equivalent diameter, and viscosity.

$$Re = \frac{G\, D_e}{\mu} \qquad (8)$$

The equivalent diameter of the plate heat exchanger channel is defined in the equation (Claesson, 2004; Talal et al., 2017).

$$G = \frac{m}{A_f} \qquad (9)$$

$$De = \frac{4b\ *\ w}{2\,(\,b + w\,)} \qquad (10)$$

Heat transfer coefficient (hi) and the Prandtl number (Pr) were acquired by the next equations:

$$Pr = \frac{\mu\, C_p}{K} \qquad (11)$$

$$h_i = 0.2536 \frac{K}{De} Re^{0.65} pr^{0.4} \qquad (12)$$

The convective coefficient (U_D) was found:

$$\frac{1}{U_D} = \frac{1}{U_C} + R_d \qquad (13)$$

$$\frac{1}{U_C} = \frac{1}{h_i} + \frac{1}{h_{io}} \qquad (14)$$

Cost Estimation

The capital cost, operational cost, and maintenance cost of the system over the course of a year are added to determine the overall yearly cost. The following equations can be used to calculate the price of the PHE. Hamidreza Najafi and others **(**Peters and Timmerhaus, 1991)

Cost of Energy

The annual cost of energy for a plate heat exchanger for hot and cold sides is given by the following equation: (Sorour et al., 2009)

$$Total\ Energy\ Cost = \left[CII \times \frac{\Delta P}{\eta} \times \frac{operating\ hours}{year}\right]h + \left[CII \times \frac{\Delta P}{\eta} \times \frac{operating\ hours}{year}\right]c \qquad (15)$$

Pressure drops calculations

The friction performance of the surface of the plate heat exchanger can be found by the following equations (Hamidreza et al., 2011).

$$J_f = 0.6\ Re^{-0.3} \qquad (16)$$

Pressure drops in ports and pressure drops within channels caused by friction make up most of the pressure drops in heat exchangers.

As a result, (Miura et al., 2008) can be used to determine the frictional pressure drop for the hot and cold streams.

The pressure drop within plates was calculated as follows (Isabel et al., 2003).

$$\Delta P = 4j_f \frac{LP}{De}\left[\frac{\rho v_c^2}{2}\right] \qquad (17)$$

Were,

$$v_c = \frac{\text{volumetric flow rate}}{w * b * N_c} \qquad (18)$$

The number of channels per pass Nc for each fluid is defined as:

$$N_c = \frac{N_p - 1}{2} \qquad (19)$$

Where, Np is total number of plates of the heat exchanger. The number of channels per pass is equal for the two fluids.

Pressure drop in ports was calculated as follows (Martin, 1999 and Oguz, 2017)

$$\Delta P = 1.3\frac{\rho\, v_{port}^2}{2} \times N_p \qquad (20)$$

where,

$$v_{port} = \frac{m}{\rho\, A_{port}} \qquad A_{port} = \frac{\pi\, d_{port}^2}{4}$$

and d= 0.036 m

Fixed Cost

Purchased Cost

The cost of heat transfer is given by the following equations (Sorour, et al., 2009; Hamidreza, et al., 2011)

Fixed cost = Purchased cost×(1+0.6)×0.15, L (21)

Purchased cost = 75228.2($A^{0.5053}$)

where, A is the heat transfer area, m2, (1+0.6) is the cost of installation and maintenance, 15% is the depreciation cost.

Annual Total Cost

The Annual total cost is simply the sum of the annual costs of energy and fixed cost.

Total cost = Cost of energy + Fixed cost (22)

3. Results and Discussion

The trade-off between pressure drop and heat transmission occurs during heat exchanger optimization. A higher flow velocity typically translates into a higher heat transfer coefficient, a smaller heat transfer area, and, thus, a cheaper capital cost. However, more velocity will result in a greater pressure drop, which will increase power consumption and raise the cost of power (Muralikrishna and Shenoy, 2000)

A Case Study and Optimized Results

It is required to cool 1.4166 kg/s of soybean milk from 90˚C to 4˚C; using chilled water 12.358 kg/s at 1˚C, the performance plate heat exchanger data are available (Agricultural Research Center,2018) as shown in Table 1.

Dimensions of plate are (0.18 × 0.62 m^2)

Spacing between plates is 0.5 cm.

gap between plates, b=0.002m

R_d is taken to be 0.0006 h.m.^{o}c/kCal

Table 2. shows the physical properties of the hot and cold fluids and are evaluated at bulk temperature according to equation 3 and 4.

Table 1. Performance data of plate heat exchanger used in soy-bean milk process.

Property	Soy bean milk Hot side	Chilled water Cold side
Inlet temperature, °C	90	1
Outlet temperature, °C	4	11
Bulk temperature, °C	47	6
Mass flowrate, K_g/s	1.4166	12.358
Equivalent diameter, m	0.00395	
Reynolds number	657.08	20544.65
Prandtl number	38.47	9.515
Convective heat transfer coefficient, h, K_J/ m.s.°C	9760.99	64320.57
Over all heat Transfer rate,U_D, K_J/m.s.°C	1392.76	
Heat Transfer rate (Q), K_J/s	32504.21	
Number of plates	11	
Velocity, m/s	3.82	

Table 2. Show the physical properties of soybean milk and chilled water. Fluid properties (ρ, μ, Cp)

Property	Values for soybean milk, Hot side	Values for chilled water, Cold side
μ (Kg/m. s)	$4.731*10^{-3}$	$1.32*10^{-3}$
ρ (Kg/m^3)	1020	1000
Cp (J/K_g. k)	4240	4180
K (w/m. K)	0.52	0.64

In real-world applications, heat exchangers must meet a number of requirements, and to transmit fluid flow across the heat exchanger's passageways, pumping power must be consumed. The relationship between volumetric flow velocity and the annual costs of area, power, and total cost is depicted in Figure 2. The findings indicate that the ideal flow rate for milk was around 2.25 m/s, with an annual total cost of 35,000 L.E.

The link between the quantity of plates, area cost, power cost, and overall annual cost is depicted in Figure 3. According to the findings, 17 plates were the optimum amount to employ in the plate heat exchanger during the production of soy milk.

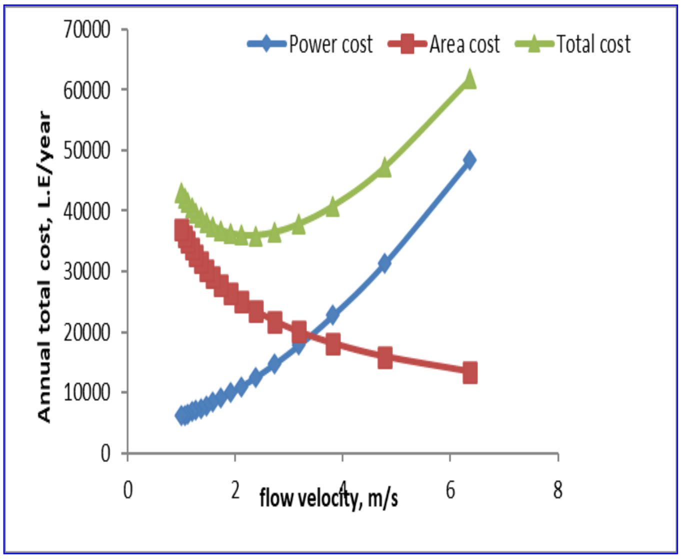

Figure 2. Relationship between flow velocity, area cost, power cost and total annual cost

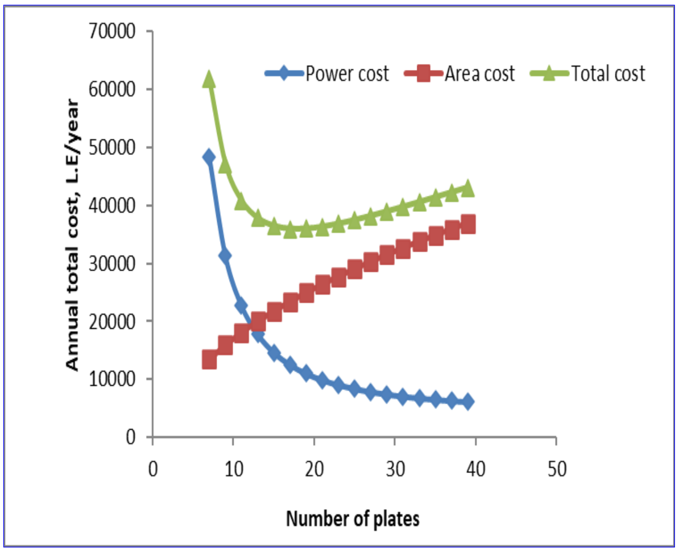

Figure 3. Relationship between Number of Plates, Area Cost, Power Cost, and total annual cost

4. Conclusion

In a plate heat exchanger, flow velocity and plate count are optimized. A case study has been provided to demonstrate the results of optimization. For both fluids, pressure drops, heat transfer coefficient, and Reynolds number were calculated. For an annual production rate of 43797.65 m^3/year, it was discovered that the minimum flow velocity is 2.25 m/s, the ideal number of plates is 17, and the minimal total yearly cost is 35000 L.E./year.

5. Nomenclature

Q: heat exchange rate, W
m: flowrate, k_g/s
T: temperature, ºC
$C_{p:}$ specific heat (k_J/ k_g. K)
Tb: bulk temperature, ºC
ΔT_m: is the log-mean of the temperature difference.
A: heat transfer area, m^2
G: mass velocity, kg/hr.m^2
De: equivalent diameter, m

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