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Fouling threshold model of plate heat exchangers for use in the dairy industry

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Abstract

Fouling of heat exchangers in the food industry is one of the major industrial problems because, in addition to increasing the pressure drop, increasing the cost of cleaning, and sometimes even replacing the converter, it also causes the growth of microorganisms in the deposited areas. This issue is extremely important in various industries, especially in the dairy industry. In this paper, two very important parameters, including mass temperature and fluid velocity in fouling rate, were investigated using MATLAB software. In this study, it was shown that increasing the temperature of the fluid increases the deposition. The results showed that with increasing the temperature by 20 degrees, the amount of output protein concentration decreased by 77%. Also indicates a decrease in fouling, and since the formation of fouling causes resistance on the surface of the converter plates, an increase in fouling reduces heat transfer and consequently a decrease in the overall heat transfer coefficient. The effect of increasing the concentration of dense protein in the thermal boundary layer is that the concentration of this protein affects the dimensionless number Bi and increasing it reduces the overall heat transfer coefficient compared to the pure state.

Keywords: dairy industry; fouling; heat exchanger; heat transfer; fluid.

Practical Application: The formation of fouling depends on the temperature and speed of the fluid.

1 Introduction

Fouling is, in fact, the accumulation of undesirable materials (fouling) on the surface of heat exchanger pipes; these materials can be crystals, sand, gravel, polymers, cooking products, inorganic salts, and biological growth or corrosion products, all of which affect the heat transfer and fluid flow conditions of heat exchangers (Pandya et al., 2020). In general, it can be said that the appearance of fouling phenomenon leads to a decrease in thermal efficiency and an increase in pressure drop, which may also lead to corrosion and cause the heat exchangers to fail; of course, it should be noted that in certain cases, the deposit may prevent leakage from corrosion. Due to the low thermal conductivity of this fouling, their thermal resistance increases, and by reducing the performance of the heat exchanger, depending on the amount of fouling leakage, periodic cleaning is necessary. Accumulation of fouling on heat transfer surfaces increases the overall resistance to heat flux flow (Wang et al., 2020). Fouling in the heat exchangers is a main problem in the dairy industry. Fouling indeed produces a thermally insulating layer over the surface of the heat exchanger and decreases the heat transfer toward fluids, and increases the pressure downfall. Additionally, fouling can seriously decrease the quality of food products by supporting the development of harmful bacteria and thus increase the costs and environmental effects because thorough cleaning procedures have to be used (Indumathy et al., 2021).

The flow of milk through the plate heat exchanger results in the denaturation of proteins, leading to fouling. This also accelerates bacterial adhesion on the plate heat exchanger surface, eventually resulting in the development of biofilms. During protracted processing, these biofilms lead to the shedding of bacteria and cross-contaminate the milk processing, thereby limiting the time of production runs. Changing the plate heat exchanger's surface properties, including surface energy and hydrophobicity, can be reduce biofouling (Jindal et al., 2018).

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The fouling phenomenon is one of the most undesirable possible events in the world of heat exchangers and heat transfer. Fouling formation in a heat exchanger is a process that reduces the efficiency and performance of heat exchangers due to the accumulation of fouling on the heat transfer surface. The dairy industry is one industry that performs heat treatment for a wide range of fluids that tend to precipitate. Proteins, sugars, fats, and minerals are the main constituents of dairy products, effective factors in scale formation in heat exchangers (Zhang et al., 2019). Providing solutions to prevent the deposition of milk and dairy products improves heat performance and reduces costs fouling is one of the costs of cleaning and even replacing a new converter (Yibin et al., 2020).

Due to the competitiveness of the dairy market, the dairy industry is always looking for new products to reach the consumer. Various techniques for identifying consumer needs and expectations help develop new and more competitive products (Torres et al., 2020). Each of these techniques requires the use of new and different methods in processing dairy products. In the dairy industry, fouling is a very important parameter seen as it can affect the quality of food products. Studies on this phenomenon showed during milk heat treatment have led to the conclusion that protein is the main precursor of fouling (Aouanouk et al., 2018).

Shell and tube heat exchangers, as well as plate heat exchangers with different purposes and, are widely used in food, beverage (beverage, juice, etc.), and dairy industries. For example, they are used to pasteurize milk and cream and sterilize at very high temperatures. This process aims to kill the microorganisms that cause food spoilage. Heat transfer must be done quickly and efficiently to prevent damage to the nutrients in food and beverages as much as possible, as well as to save time and fuel consumption. In some applications, air-cooled converters, called dry coolers, can also be used to cool fluids instead of shell and tube or tube converters. The air conditioner drains much like a cooling radiator, and the built-in fans cool the fluid by blowing air through the coils. If one or both of the heat transfer materials are fluid (liquid or gas), they flow continuously in the exchanger, and heat exchange takes place between them with high efficiency. These transducers are often used to pasteurize milk and other beverages. The fouling of heat exchangers in the dairy industry has been investigated extensively. Various factors affect the fouling of dairy products. These factors are divided into five categories, including milk composition, operating conditions, heat exchanger characteristics, micro-organisms, and fouling location (Bansal & Chen, 2005). Research suggests that the primary step in fouling is the adsorption of proteins onto the wall of the heating equipment. Real fouling, however, is caused by particle formation in the bulk of the liquid being processed. Their formation is heat-induced, and the deposition takes place through diffusion toward the heating surface. Only very high flow rates can prevent their deposition and subsequent sticking. To control the process of fouling, special attention is given to the parameters affecting the establishment of both types of particles and how their formation can be retarded or prohibited (Visser & Jeurnink, 1997).

The direction of movement of fluids that exchange heat with each other can be in three ways: i) same direction, ii) opposite to each other, iii) cross. Each of these streams has its own characteristics. For example, in a transducer where the flow of two fluids is parallel and in the same direction, the highest heat exchange occurs at the transducer's input. To create a turbulent flow in the fluid and increase heat transfer, blades are used around the heat exchanger tubes, called finned tubes or fin tubes (Liu et al., 2018). Figure 1 shows a Shell and tube heat exchanger utilized in the food industry.

Another type of converter widely used in food processing plants is the plate heat exchanger. This converter consists of plates that are sealed relative to each other, and hot and cold fluid flow between the plates to exchange heat between them. The advantage of plate heat exchangers is the large heat transfer surface and easy access to clean the surface (Alvarez-Bueno et al., 2019). Figure 2 shows a picture of a Plate heat exchanger in the food industry.

Dasi et al. (2020), using heat exchangers, studied the effect of cooling and heating on dairy products. Ejector-based systems with and without internal heat exchangers are compared. The effects of gas cooler outlet temperature, receiver pressure, and gas pressure on the performance of the system are investigated by energy

Figure 1. Shell and tube heat exchangers in the food industry.

Figure 2. The plate heat exchanger in the food industry.

analysis. They concluded that the internal heat exchanger not only reduces the minimum air conditioner pressure required for the pasteurization temperature but also increases the efficiency of the COP and exergy systems by 6.4% and 4.5%, respectively. Also, the analysis of the second rule shows that the maximum exergy efficiency of the system is 38.4%. Indumathy et al. (2021) investigated the steady-state and transient performance of the high Temperature-Continuous-Pasteurization-Process (HTST). The conservation of energy and mass is applied in modeling the milk plant. Modeling of heat exchanger is improved using Log-Mean-Temperature-Difference (LMTD). Results showed that the reduction of 0.5 °C in pasteurized milk temperature approximately reduces the quality of milk.

2 Material and methods

Fouling on the surfaces causes resistance to heat flow, pressure drop, and reduction of the converter efficiency and will be economically detrimental to the food producer. Its purification is more important than other industries in the food, beverage, dairy, health, and pharmaceutical industries. In other industries, the converter is usually cleaned once a year, but in the food industry, cleaning is usually done every day (Kakani et al., 2020). Today, many methods are used for descaling, some of which are applied by the manufacturer and some by customer information and experiences so that the converter always works with maximum efficiency and there is no health problem.

For example, one of the most important is that the fluids inside the converter have turbulent flow instead of slow flow. The turbulent flow created by the velocity and change in the geometry of the transducer and automatically prevents the formation of fouling and causes the particles adhering to the wall to separate. Other methods include physical, chemical, magnetic, thermal descaling, the use of high-tech coatings on surfaces, and so on. One of the important points is that in addition to water, food or beverage products should also be free of great materials to prevent the formation of a bridge between the plates and its burning and to prevent the deposition of food on the plates and pipes. One of the important factors in increasing the efficiency of the heat exchanger is to prevent the accumulation of mineral or organic particles on the surfaces of the heat exchanger so that there is no obstacle to heat transfer. Therefore, if water is used as a heat transfer fluid, it must be deionized (van der Hoek et al., 2018).

2.1 Effective factors in fouling formation

One of the most important factors affecting the formation of fouling is the fluid's temperature and velocity. A gentle and static flow can allow fouling to easily stick to the surface and form. High speed reduces and minimizes all types of fouling. Despite these high speeds, it requires high pump power, which may cause surface wear. On the other hand, the temperature of the fluid and the heat transfer coefficient of the fluid and the precipitating substance will determine the temperature of the common surface of the two (Fryer & Slater, 1985). In this paper, the dynamic model of milk fouling presented by Georgiadis & Macchietto (2000) was used to investigate the factors affecting fouling formation.

Milk protein is the first native, then denatured protein, and finally, dense protein and only the dense protein in the thermal boundary layer can precipitate. According to the primary protein, it is denatured by a first-degree reaction and densified by a second-degree reaction. This paper investigated two very important parameters (mass temperature and fluid velocity in fouling rate) using MATLAB software.

3 Results and discussion

In this study, it was shown that increasing mass temperature reduces the output protein concentration and decreases the protein concentration at the output. The channel indicates that more protein is produced in the compacted state, so increasing the temperature of the fluid increases the precipitation. Figure 3 shows the changes in the concentration of the output protein with the change in temperature of the fluid mass.

In another study, all other parameters were kept constant, and the inlet fluid velocity was changed in several steps to show its effect on the amount of dense protein. Figure 4 shows the rate changes with dense protein concentration. Due to the increase in velocity, it reduces the concentration of dense protein in the thermal boundary layer, which indicates a decrease in fouling. The fouling thickness according to the fryer and slater relationship is shown in Figure 5.

3.1 The effect of fouling on the overall heat transfer coefficient

Since fouling formation causes resistance on the surface of the converter plates, increasing fouling reduces heat transfer and consequently reduces the overall heat transfer coefficient. The increase in fouling is due to the increase in the concentration of dense protein in the thermal boundary layer. The concentration of this protein affects the dimensionless number Bi and its increase reduces the overall heat transfer coefficient compared to the clean state (Mahdi et al., 2009). Figure 6 changes in the overall transfer coefficient show the heat after about 6 h for milk with the physical condition.

The proposed fouling model in the food industry is as Equation 1.

$$\frac{dm}{dt} = aR_e^b \exp\left(-\frac{E}{RT_b}\right) - cR_e^d \quad (1)$$

In this model, the amount of fouling mass changes was used instead of fouling resistance, and the dependence of fouling formation term with Arianus relationship by fluid mass temperature is expressed. The fixed coefficients of this model are different for different types of milk. To calculate the fixed coefficients in this paper, Christian laboratory data are given in Table 1 were used. These data are in the field of calcium deposition in milk (Christian & Fryer, 2003). In Table 1, T represents the temperature, Re represents the gas constant, and dm/dt represents the changes in the mass deposition to time changes.

Finally, by setting the first side equal to zero ($d_m/d_t = 0$) (Wilson et al., 2010), the fouling curve for calcium in milk was presented as Figure 7. At points where the transducer is above

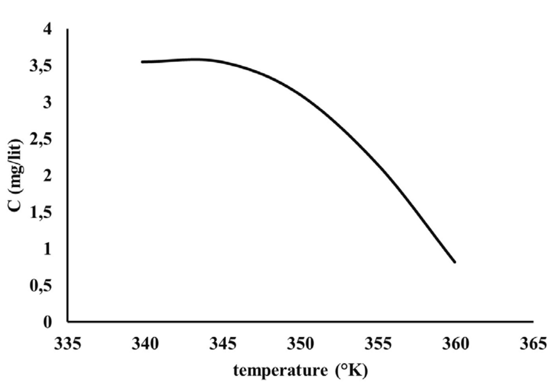

Figure 3. Changes in the output protein concentration with changes in fluid mass temperature.

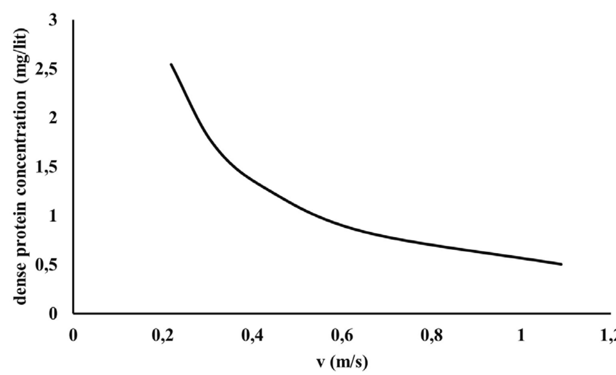

Figure 4. Velocity changes with dense protein concentration.

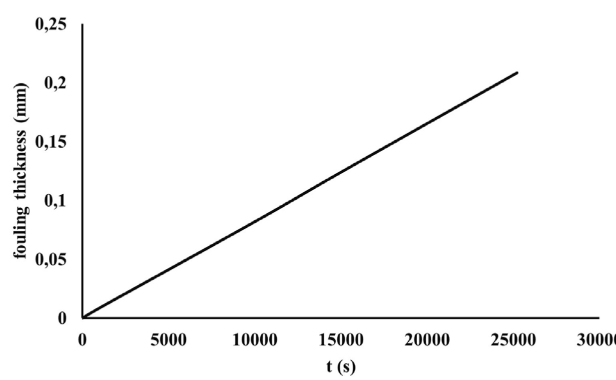

Figure 5. Fouling thickness changes with time.

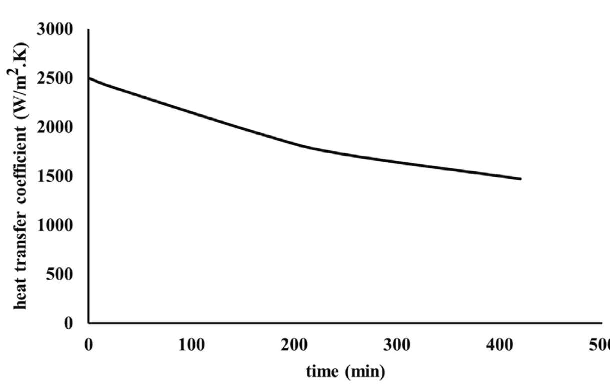

Figure 6. Changes in the overall heat transfer coefficient with time.

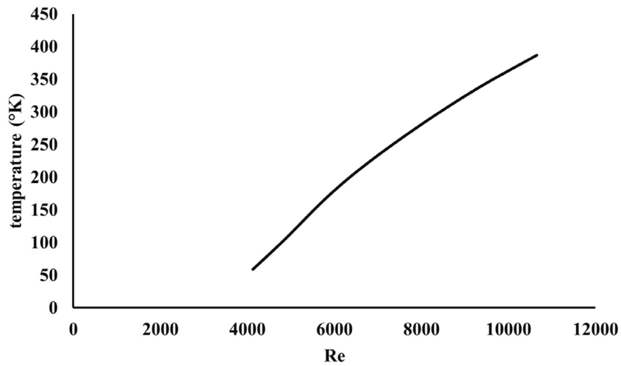

Figure 7. Fouling curve for calcium in milk.

Table 1. Laboratory data of milk calcium deposition.

T (°K)	Re	d_m/d_t
362.7	3987.95	0.32528
362.7	3795.25	0.55105
362.3	3776.45	0.65163
362.8	3797.6	0.78003
362.8	5802.15	0.29211
363.1	5781	0.30495
362.5	5806.85	0.37771
362.8	5788.05	0.59599

Table 2. The numeric value of Re in threshold mode.

Re (threshold)	**T (°k)**
5064.829028	340
5993.288366	345
7057.923981	350
8273.484281	355
9655.681474	360
11221.1976	365
12987.68678	370

the threshold curve, it indicates that it has been exposed to fouling. Numeric values of Re in threshold mode for different temperatures are shown in Table 2.

4 Conclusion

This paper investigated two very important parameters (mass temperature and fluid velocity in fouling rate) using MATLAB software. In this study, it was shown that increasing mass temperature reduces the output protein concentration and decreases the protein concentration in the channel output indicates that more protein is produced in the condensed state, so increasing the temperature of the fluid increases the deposition. Also increasing the velocity reduces the concentration of dense protein in the thermal boundary layer, which indicates a decrease in fouling.

Since the formation of fouling causes a resistance on the surface of the converter plates, increasing fouling reduces heat transfer and consequently reduces the overall heat transfer coefficient. The increase in fouling is due to the increase in the concentration of dense protein in the thermal boundary layer. The concentration of this protein affects the dimensionless number Bi and its increase reduces the overall heat transfer coefficient compared to the clean state.

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