

Electric field effect on the milk fouling resistances in shell and tube heat exchangers

Gövde borulu ısı değıştircilerde süt kirlenme dirençleri üzerinde elektrik alanının etkisi

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ABSTRACT

In the present study, the effect of both electric field and surface charge on thermal fouling resistance was investigated during the milk pasteurization process in a laboratory-scale shell and tube heat exchanger. Fouling resistances were calculated by the LMTD (Logarithmic Mean Temperature Differences) method. Foulant fluid was milk, and its flow rate was constant at $750.10^{-6} \text{ m}^3 \text{ min}^{-1}$ (Reynolds number = 214.37). Applied electric field strengths were 4000 V m^{-1} , 8000 V m^{-1} , and 12000 V m^{-1} between the shell side surface of the heat exchanger and a cable passed through the inside tubes of the heat exchanger. It was observed that fouling was reduced when a 4000 V m^{-1} electric field was applied to the positively charged heat exchanger surface. No major change in fouling resistance was observed for other applied electric field and surface charge conditions.

Keywords: Fouling, Electric field, Milk processing, Thermal resistances.

Öz

Mevcut çalışmada, laboratuvar ölçekli bir kabuk-borulu ısı değıştircisinde süt pastörizasyon işlemi sırasında hem elektrik alanının hem de yüzey yükünün termal kirlenme direncine etkisi araştırılmıştır. Kirlenme dirençleri LMTD (Logaritmik Ortalama Sıcaklık Farkları) yöntemi ile hesaplanmıştır. Kirletici akışkan süt olup, akış hızı $750.10^{-6} \text{ m}^3 \text{ dak}^{-1}$ de sabittir (Reynolds sayısı = 214.37). Isı değıştircinin kabuk tarafı yüzeyi ile ısı değıştircinin iç borularından geçen bir kablo arasında uygulanan elektrik alan şiddetleri 4000 V m^{-1} , 8000 V m^{-1} ve 12000 V m^{-1} dir. Pozitif yüklü ısı değıştirci yüzeyine 4000 V m^{-1} lik bir elektrik alanı uygulandığında kirlenmenin azaldığı gözlenmiştir. Diğer uygulanan elektrik alanı ve yüzey yükü koşullarında kirlenme direncinde önemli bir değışiklik gözlenmemiştir.

Anahtar Kelimeler: Kirlenme, Elektrik alanı, Süt işleme, Isıl dirençler.

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Introduction

Investigation of anti-fouling techniques has received much attention in the past and a variety of chemical and mechanical methods have been suggested to reduce the formation of a deposit on heat transfer surfaces. However, mechanical methods, such as pipe inserts or circulating sponge balls, are costly and usually limited to the inside of pipe-like geometries. For Plate Heat Exchangers (PHEs), only chemical mitigation is possible. Unfortunately, using chemical additives may cause undesired product contamination or have adverse effects on the environment (Beuf et al., 2003).

Several authors have investigated non-chemical methods for preventing/reducing fouling on surfaces, such as;

- Altering the surface properties of the heating surfaces (Beuf et al., 2003; Zhao et al., 2002; Karlsson et al., 1996; Yoon et al., 1994; McGuire, 1987),
- Using pulsed flows (Gillham et al., 2000; Polte, 1987), creating magnetic fields (Yoon et al., 1994),
- Oscillating electric fields using time-varying magnetic fields generated in a solenoid wrapped around a feed pipe carrying water (Cho et al., 1998; Lee et al., 2002) and,
- Ohmic heating processes (Ayadi et al., 2005), high pressure processing (Gracia-Julia et. al., 2008).

Another non-chemical method is the use of electric fields in heat exchangers for reducing milk fouling. There are two different methods for the use of electric fields for the fouling of heat exchangers. In the first method, the milk is subjected to a small direct or alternating electric current before it reaches the heat exchanger, or it is passed through a strong magnetic field, which produces similar currents by induction. In the second one, the heating surface is made one pole of an electric circuit so that local changes are caused at the surface. The second method has been found useful in preventing cheese curd adhesion to the vat surface (Burton, 1968).

Understanding the effect of electric field direction requires an explanation about formation of milk fouling. In dairy processes, fouling of heat exchangers is arises from the complex milk content including minerals, proteins, whey and other constituents such as lactose and their reactions or interactions during heating of milk for pasteurization (Huppertz & Nieuwenhuijse, 2022). During heating of milk in a heat exchanger an undesirable deposit, mainly consisting of protein and mineral, is formed on the heating surface. Excess mineral ions such as calcium and magnesium in the milk are believed to precipitate into mineral salts, forming nucleates for later crystal growth. Even at room temperature, a monolayer of protein is immediately adsorbed. Further deposition of protein on top of this monolayer occurs if serum proteins undergo heat denaturation. Then so-called activated β -lactoglobulin (β -lg) molecules are formed in the bulk (Jeurnink et al., 1996b).

Skudder et al. (1981) showed the importance of aggregation in fouling, which could be significantly decreased by adding potassium iodate to milk before pasteurization. This oxidizes the sulfhydryl (-SH) groups exposed during β -lactoglobulin denaturation, preventing aggregation. Conversely, increasing the concentration of reactive -SH groups by adding L-cysteine -HCl to milk before pasteurization increased fouling.

Jeurnink et al. (1996a) suggested that the deposition of an activated molecule by a reaction with an already deposited molecule, most probably through the formation of a disulfide bond, is a step of the deposition process on top of an adsorbed monolayer.

According to Changani et al. (1997), fouling can be modelled by using data on the thermal behavior of β -lactoglobulin, coupled with models for the flows and temperatures of the process plant. Anema and McKenna (1996) described the denaturation of β -lg as a two-stage consecutive process, comprising unfolding of the molecule followed by aggregation.

Both the schematic diagram of the heat denaturation of β -lg according to Roefs et al. (1994) and the schematic representation of the dissociation, unfolding, and aggregation of β -lg and the consequences for deposition in the absence of calcium phosphate according to Visser et al. (1997) are inspected there is a question arising;

“Whether the motion of activated β -lactoglobulin (β -lg) molecules which have free -SH groups could be affected by an electric field or not? Are they repelled or attracted by surface?” So the aim of this study is preventing deposition of activated β -lg molecules on top of protein monolayer. Therefore, the fouling resistances were measured and compared for the following cases;

- with an electric field and surface charge applied to shell and tube heat exchanger,
- without an electric field or surface charge (neutral surface)

The effect of electric field direction, so the effect of surface charge (+ or -) was also investigated.

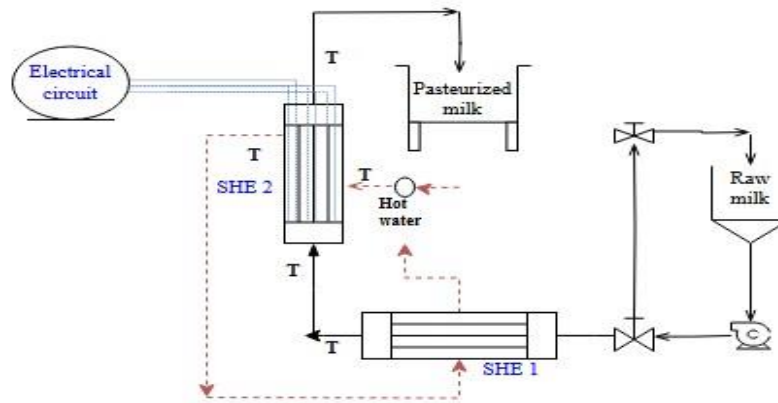
Methods

During the experiments, the whole milk obtained from Atatürk University's dairy factory, 4 hours after milking of cows taken as foulant fluid, passed through a shell and tube heat exchanger during 25-30 minute periods. Milk was prepared by adjusting its fat ratio to 3% and pH to 6.3-6.4 if necessary.

Korkut et al. (2003) have studied the effect of milk velocity on the thermal resistances, and they found that the thermal resistances were the minimum at $750.10^{-6} \text{ m}^3 \text{ min}^{-1}$ for the laboratory scaled shell and tube heat exchanger, whose tube layout is square pitch (90° angle). So in this study, the fouling resistances were measured at $750.10^{-6} \text{ m}^3 \text{ min}^{-1}$, a constant flow rate of milk in the same laboratory scaled shell and tube heat exchanger, with a square pitch (90° angle).

Figure 1.

Continuous flow for the milk pasteurization system.



Note: C: Container, F: Flowmeter, P: Pump, SHE1: Pre-heater (shell and tube heat exchanger), SHE2: Pasteurizer (shell and tube heat exchanger), T: Thermocouple reading points, V_s : Steam flow control valve, V_f : Feeding fluid flow control valves, G: Power supply

Schematic diagram of continuous flow for milk pasteurization system has presented in Figure 1. The flow rate of the milk through the system was given the Reynolds number = 214.37 by a flow meter (KI FR-4000 series, 4L53 Model, Key Instruments Co., USA). Circulation of the milk through the system was facilitated by a pump (Model PP 215 A, Tarpo Co., Turkey) to inner tubes which were heated from the shell side by hot water (inlet temperature 97°C , flow = 4.5 L h^{-1}) co-currently. A steam generator was used to heating water (ME Type, LABSCO, Germany). The inlet temperature of milk for SHE1 and SHE2 was 20°C and 36°C , respectively. The outlet temperature of the milk was 72°C .

To calculate the fouling resistance from the overall heat transfer coefficient by log-mean-temperature-difference (LMTD) method (Incropera, 1996), temperatures were measured at four different positions of heat exchanger (milk inlet and outlet, and hot water inlet and outlet), by Ni-CrNi thermocouples (Elimko Co., Turkey) and monitored by Sistek Instrument (TRC-6 Model, Sistek Co., Turkey) as seen in Figure 1.

The shell side of the heat exchangers was ID = 7.1 cm and consisted of 9 tubes (each tube ID = 1 cm). Heat exchangers' stainless steel surface was charged positively (+) or negatively (-) for preventing deposition of activated β -lg molecules, including free -SH groups and salts. Also, an electric field is produced by a silicone-covered copper wire passed through the tubes of the heat exchanger. The copper wire ($d = 1.5 \text{ mm}$) covered with silicone (outside $d = 2.5 \text{ mm}$) is inserted into the heat exchanger, as shown in Figure 1. Copper wire and the heat exchangers' surface were connected to the positive (+) or negative (-) pole of a DC electrical power supply. The strengths of the electric fields were 4000 V m^{-1} , 8000 V m^{-1} , and 12000 V m^{-1} generated between the surface of the heat exchanger and the cable passed through the inside of the tubes of the heat exchanger by applying a voltage ranging from 0 – 50 V. The magnitude of the electric field is calculated with the formula (Yalçın, 1986);

$$E = V/d \quad (1)$$

where V is the applied potential and d is the distance between the two poles. According to Gauss's law, the excess charge on an isolated conductor accumulates on the outer surface of the conductor. Therefore, the outer diameter of the cable passing through the heat exchanger is taken into account in the calculations. Two experiments were conducted for all electric field strengths while altering the polarity of the heat exchanger surface to positive (+) or negative (-).

Results and Discussion

Charge Effects of Heat Exchanger Surface on Fouling Resistances

When Figure 2 examined it can be seen that at (-) charged heat exchanger surface under 4000 V m^{-1} electric field caused much fouling. This can be arisen from the effect of direction of electric field. It is known that electric field lines always begin on positive charges and end on negative charges. So the electric field directions always towards to the negative charged surfaces from the positive charged surfaces as seen in Figure 3. Thus, the transportation of aggregates from bulk to the surface gets easier and fouling resistances are increased. Conversely, under 8000 V m^{-1} and 12000 V m^{-1} electric fields in Figure 4 and Figure 5, there is no difference between fouling resistances which are belong to (+) charged, (-) charged and neutral surfaces. In this case, because of the opposite directions of generated electric fields and formed static attractive fields, the motions of $-SH$ groups may not be affected by surface charge.

Figure 2.

Variation of fouling resistances with time during pasteurization of milk while applying 4000 V m^{-1} electric strength at various charged surfaces.

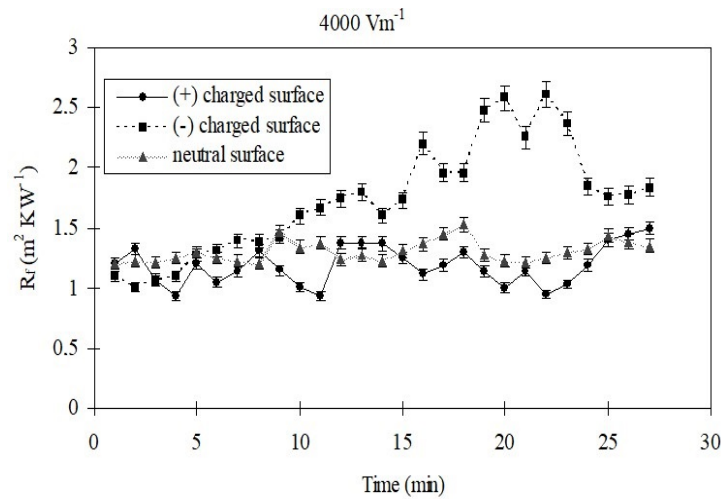
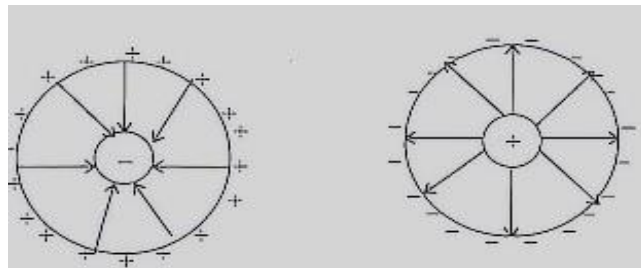


Figure 3.

Direction of electric fields (The inner circle represents the cable and the outer circle represents the pipe surface).



Effects of Electric Field Strengths on Fouling Resistances

Figures 6 and 7 show the effects of electric field strengths on fouling resistances. In Figure 6, fouling resistances, so the deposit formation, are increasing while the electric field strengths increasing 4000 to 12000 V m^{-1} . The attractive fields generated by positive charged surface to negative charged $-SH$ groups, are strengthened by increasing electric field strengths. However, in Figure 7, there is no difference between fouling resistances like in Figure 4 and Figure 5 because of the same opposite effects.

The reproducibility of the results can be seen from the initial values in Figures 2, 3, 4, 5, and 6. The initial values were taken when the system reached its steady state. It is known that even at room temperature, a monolayer of protein is

immediately adsorbed on the surface. Because the milk was pumped into the tubes during the initialization process the first value of the fouling resistances is greater than zero, and all the values are approximately equal.

Figure 4.

Variation of fouling resistances with time during pasteurization of milk while applying 8000 V m^{-1} electric strength at various charged surfaces.

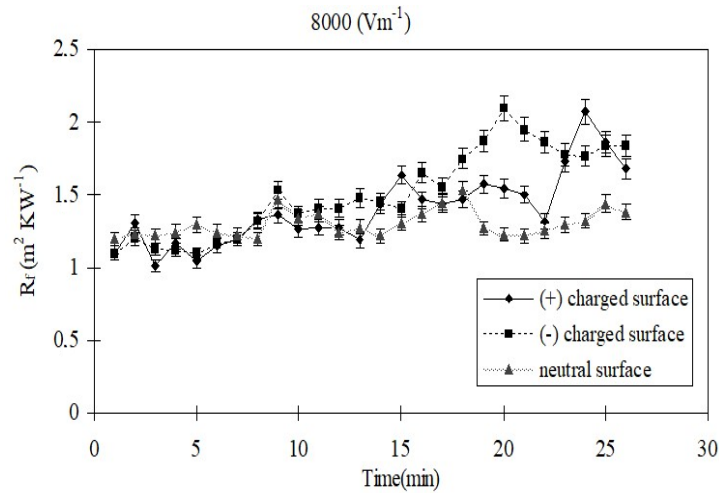


Figure 5.

Variation of fouling resistances with time during pasteurization of milk while applying 12000 V m^{-1} electric strength at various charged surfaces.

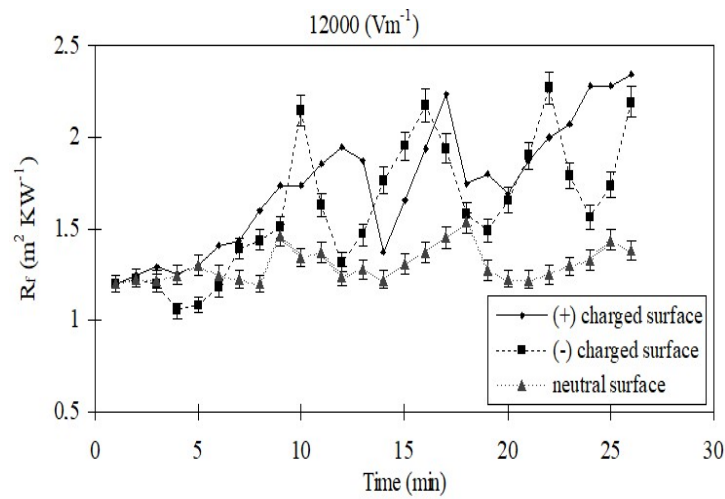
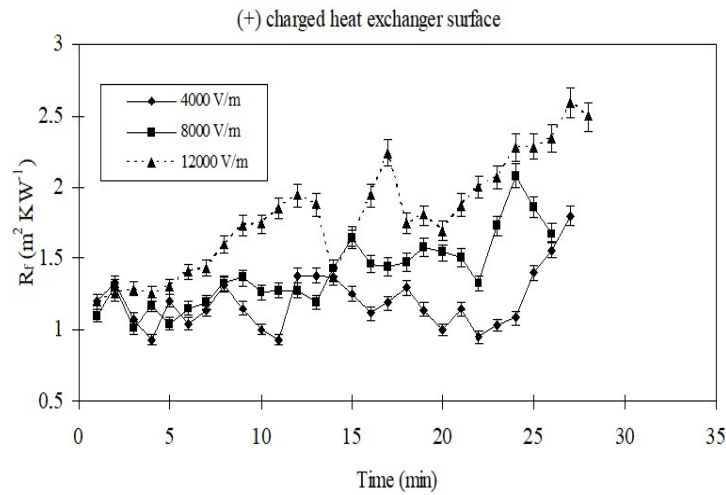
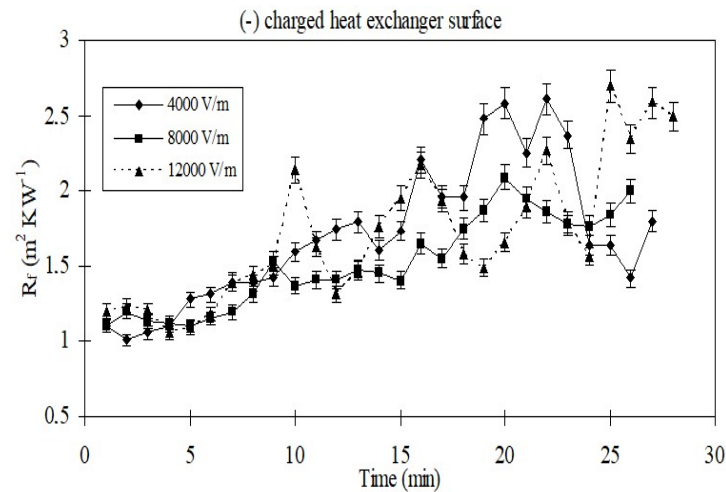


Figure 6.

Variation of fouling resistances with time during pasteurization of milk at (+) charged heat exchanger surface under various electric field strengths.

**Figure 7.**

Variation of fouling resistances with time during pasteurization of milk at (-) charged heat exchanger surface under various electric field strengths.



Conclusions

This article aims to investigate the effects of positive or negative charging of the heat exchanger surface and the creation of an electrical field within the heat exchanger on the fouling resistance during milk pasteurization. The examination of results indicates that employing electric fields to prevent milk fouling is ineffective, except for the positively charged heat exchanger surface at 4000 V m⁻¹. Furthermore, it may be advisable to avoid this application due to the extra costs associated with integrating it into existing systems, as well as potential issues like abrasion and corrosion on the heat exchanger surface when positively charged. However, future studies could explore the application of an electrical field prior to milk entering the heat exchanger and its impact on fouling resistance.

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