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Organic and Inorganic Fouling at Quartz–Liquid Interface in Ultraviolet Photoreactors During On-Line Sterilization of Cheese Whey

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Abstract

This article reports on lamp fouling during on-line ultraviolet (UV) sterilization of cheese whey. The extent of fouling as well as the composition of fouling materials was studied after the operation of three tubular UV reactors of different flow thicknesses (18, 13, and 6 mm) for 48 h at a 2-h residence time. Lamp fouling, which significantly affected the sterilization efficiency, was realized after an extended period of operation. The extent of lamp fouling increased with a decrease in the thickness of the flowing cheese whey (14.42, 15.31, and 25.25 g for 18-, 13-, and 6-mm thickness, respectively). A strong relationship between the extent of fouling and the steady-state outlet temperature was observed. The fouling material contained 63.51 to 77.19% protein, 12.57 to 16.49% fat, and 6.51 to 9.47% minerals on dry weight bases compared with 1% protein, 0.5% fat, and 0.4% minerals in raw cheese whey. The organic and inorganic material concentrations in the fouling material increased with a decrease in the flow thickness. The fouling mechanism was owing to adsorption and direct ion exchange, which were enhanced by the high temperature and low pH attained in the study. Improved designs of UV reactors in which the contact between the flowing material and the quartz surface should be developed.

Index Entries: Ultraviolet radiation; sterilization; cheese whey; lamp fouling; protein; fat; minerals; temperature.

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Introduction

Cheese whey is a byproduct from the manufacture of cheese or casein, which contains about 4.4 to 5.0% lactose, 0.6 to 1.0% protein, 0.1 to 1.0% fat, 0.5 to 1.0% salts, and 0.1 to 0.8% lactic acid *(1)*. The total world production of cheese whey was approx 139.6 million metric tons in 2000 *(2)*. Whey disposal creates pollution problems in regions where there are a large number of cheese producers because of its high contents of lactic acid, organic and ammonium nitrogen, biological oxygen demand (BOD) (40,000 mg/L), and chemical oxygen demand (COD) (60,000 mg/L) *(3)*. Whey can be used as a low-cost fermentation substrate for producing value-added products such as lactose *(4)*, single-cell protein *(5)*, whey protein concentrate *(6)*, methane *(7)*, alcohols *(8)*, organic acids *(9,10)*, biopolymers *(11)*, human food *(12)*, whey beverages *(13)*, whey powder *(14)*, animal feed *(15)*, fertilizers *(16)*, and de-icers and anti-icers *(17)*.

To produce a pure fermentation product, cheese whey must be sterilized. Although steam and dry heat sterilization techniques have been used successfully for various media *(18)*, such high-temperature techniques are known to denature cheese whey protein *(19)*. Because of its germicidal effect, UV radiation has been used in many applications including disinfection of drinking water *(20)*, sterilization of water in aquaculture facilities *(21)*, sterilization of medical devices *(22)*, disinfection of air *(23)*, and sterilization of polymeric materials *(24)*. Low-pressure mercury lamps are the principle means for generating UV energy because 85% of the light output is nearly monochromic at a wavelength of 253.7 nm, which is within the optimum range for germicidal effects *(25)*. UV radiation was found to be a good alternative to pasteurization of cheese whey because it shortens sterilization time, it is considered an inexpensive technique, and it can be used on-line in continuous-mode fermentations *(26)*. However, a potentially serious problem in UV disinfection systems is the accumulation of fouling materials at the quartz–liquid interface, which can reduce the effectiveness of the UV disinfection process *(27)*.

The objectives of the present study were to investigate the susceptibility of a UV lamp to fouling during on-line cheese whey sterilization, to test the effect of the flowing material thickness on lamp fouling, and to investigate the characteristics and composition of the fouling material and the nature of the fouling mechanism.

Materials and Methods

Reactors

The experimental setup consisted of a 6-mm-thick Plexiglas continuously stirred feed tank of about 10-L volume, a variable speed modular peristaltic pump (Digi-Staltic, Masterflex® Model No. 7525-30, with Head Model No. 7024-20 and Tubing No. 6404-24; Barnant, Division of Cole-Parmer, Barrington, IL), three UV reactors, and a 3-mm-thick Plexiglas overflow tank of about 25-L volume (Fig. 1).

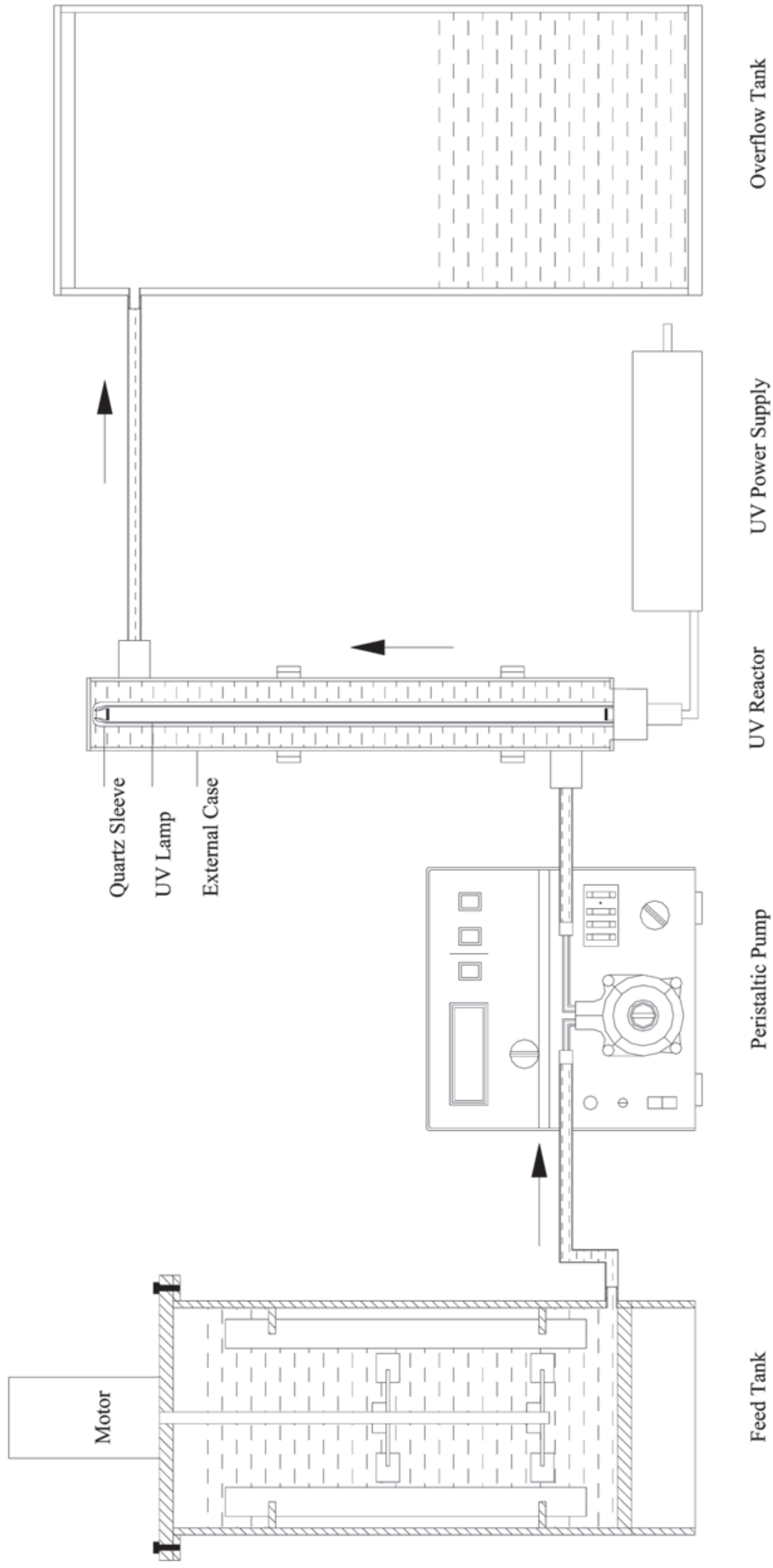

Fig. 1. Experimental setup.

A 380-mm arc length low-pressure mercury lamp enclosed in a 21-mm-diameter (od) quartz tube was used with three UV reactors (Fig. 2). The first UV reactor had an 1100-mL working volume and a 3-mm-thick stainless steel chamber of 455-mm length and 62.5-mm id, allowing a flowing material thickness of 18 mm. The second UV reactor had a 698-mL working volume and a 1.34-mm-thick stainless steel chamber of 467-mm length and 47.4-mm id, allowing a flowing material thickness of 13 mm. The third UV reactor had a 201-mL working volume and 4.3-mm-thick stainless steel chamber of 475-mm length and 33-mm id, allowing a flowing material thickness of 6 mm. An inlet port, located at the bottom part of each reactor, was connected to a peristaltic pump, which pumped the cheese whey from the feed tank. The outlet port, located at the top of each reactor, was connected to the overflow tank.

Experimental Procedure

The cheese whey used was obtained from Farmer's Cooperative Dairy Plant in Truro, Nova Scotia, in 60-L plastic containers. The containers were transported to the biotechnology laboratory where they were stored in a freezer at –25°C until used. Prior to using the cheese whey, it was first allowed to thaw completely at room temperature and was then transferred to the feeding tank. Table 1 provides some characteristics of the cheese whey.

The UV lamp was washed with a piece of cotton using tap water and laboratory detergent and then rinsed thoroughly with deionized distilled water. Raw cheese whey was pumped through the UV reactors at the required flow rates using a variable speed pump. The three UV reactors were allowed to operate at a 2-h residence time, as recommended by Mahmoud and Ghaly *(26)*. This gave flow rates of 0.55, 0.30, and 0.10 L/h for the first, second, and third UV reactors, respectively. The reactors were operated for 48 h. The outlet temperatures of the three UV reactors were continuously monitored. After each run, the lamp was carefully removed from the reactor for visual inspection, and the fouling materials were scraped and placed in small plastic containers. The containers were sealed with Parafilm and kept in a refrigerator at 4°C until needed for analysis.

Both raw cheese whey and fouling materials were analyzed for protein, fat, and trace elements (magnesium, calcium, manganese, potassium, sodium, iron, sulfur, phosphorus). The solids, lactose and nitrogen, COD, BOD, and pH analyses were performed on the raw cheese whey. The moisture content and the total weight of fouling materials were determined. Analyses of the solids, moisture, COD, and BOD were performed according to the procedures described in *Standard Methods for the Examination of Water and Wastewater (28)*. Lactose was determined using a sugar analyzer (YSI Model 27; YSI, Yellow Springs, OH). Ammonium nitrogen and total Kjeldahl nitrogen were measured using a KJELTEC AUTO 1030 Analyzer. Calculations of protein concentrations were based on a Kjeldahl factor

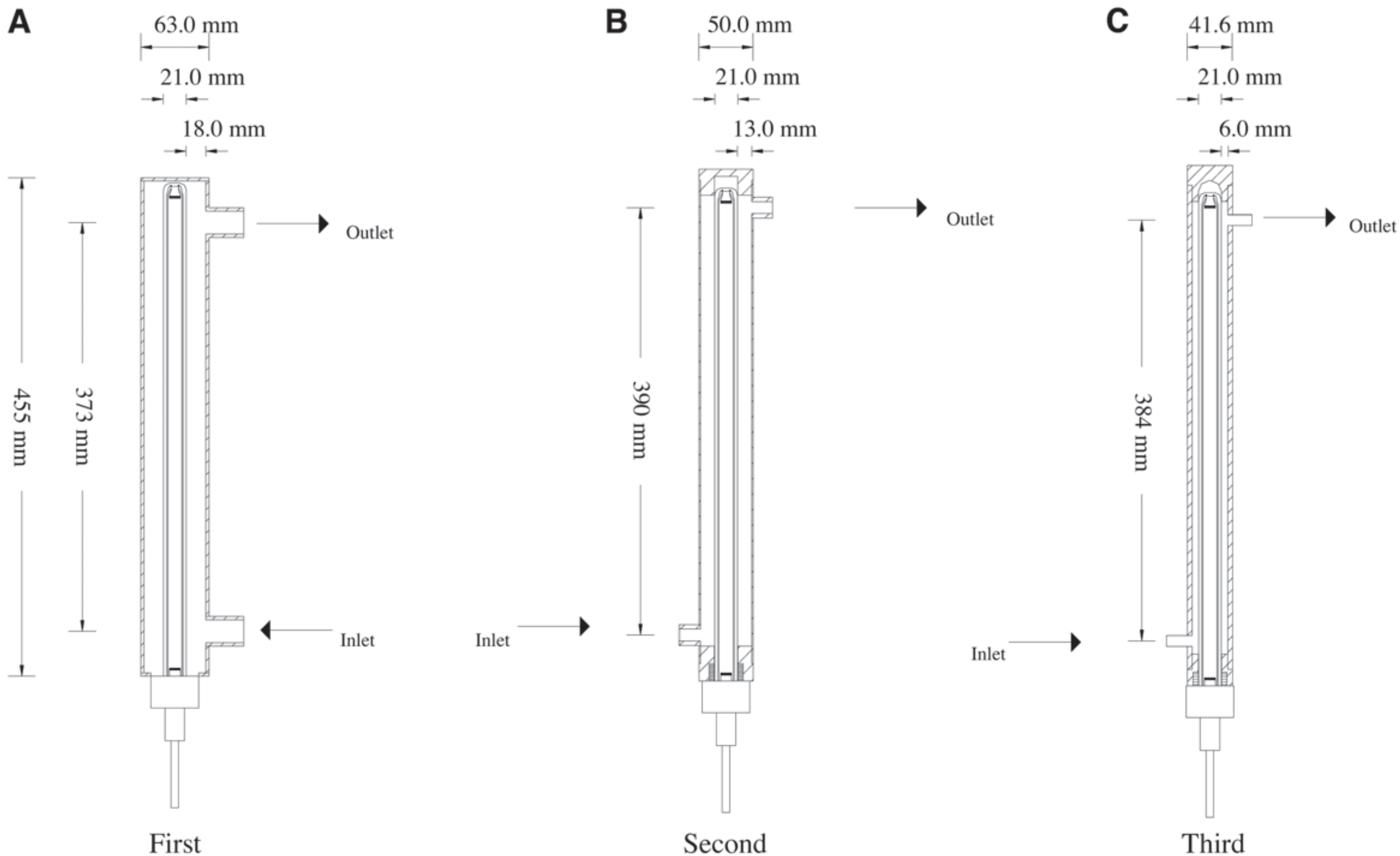

Fig. 2. Dimensions of UV reactors used: **(A)** first reactor; **(B)** second reactor; **(C)** third reactor.

Table 1
Some Characteristics of Cheese Whey Used

Characteristic	Measured value
Total solids (mg/L)	68,300
Fixed solids (mg/L)	6750
Percentage of fixed solids (%)	10
Volatile solids (mg/L)	61,550
Percentage of volatile solids (%)	90
Suspended solids (mg/L)	25,160
Fixed solids (mg/L)	230
Percentage of fixed solids (%)	1
Volatile solids (mg/L)	24,930
Percentage of volatile solids (%)	99
Total Kjeldahl nitrogen (mg/L)	1560
Ammonium nitrogen (mg/L)	260
Percentage of ammonium nitrogen (%)	17
Organic nitrogen (mg/L)	1300
Percentage of organic nitrogen (%)	83
Total COD (mg/L)	81,050
Soluble chemical oxygen demand (mg/L)	68,050
Percentage of soluble COD (%)	85
Insoluble COD (mg/L)	13,000
Percentage of insoluble COD (%)	15
BOD (BOD5) (mg/L)	52,220
Lactose (mg/L)	50,000
Fat (mg/L)	4700
Protein (mg/L)	9953
Element	
Mg (mg/L)	94
Ca (mg/L)	429
Mn (mg/L)	1
K (mg/L)	1670
Na (mg/L)	684
Fe (mg/L)	42
P (mg/L)	154
S (mg/L)	483
Others (mg/L)	3193
pH	5.00

of 6.38 *(1,29,30)*. The fat content was obtained according to the method described by Bligh and Dyer *(31)*. The trace element analyses were done in the Minerals Engineering Center of Dalhousie University. Visualization and microscale elemental analyses of the inner and outer surfaces of the fouling materials were performed using environmental scan electron microscope (ESEM) and energy-dispersive X-ray analyses at the Bedford Institute of Oceanography, Halifax, Nova Scotia.

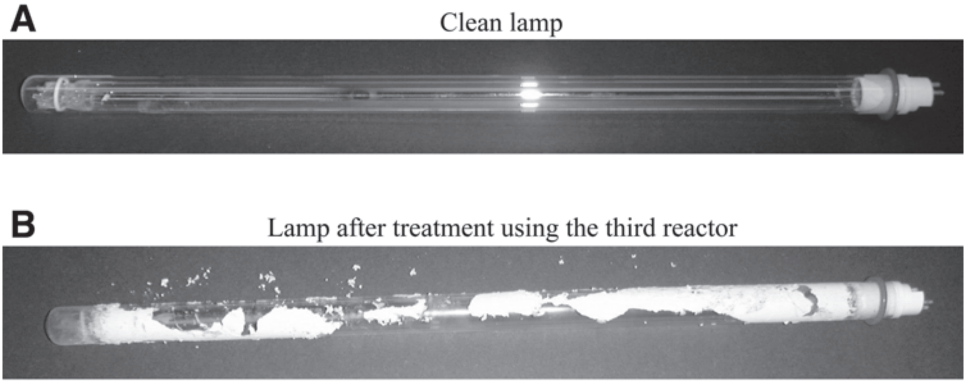

Fig. 3. UV lamp **(A)** before and **(B)** after treatment of cheese whey.

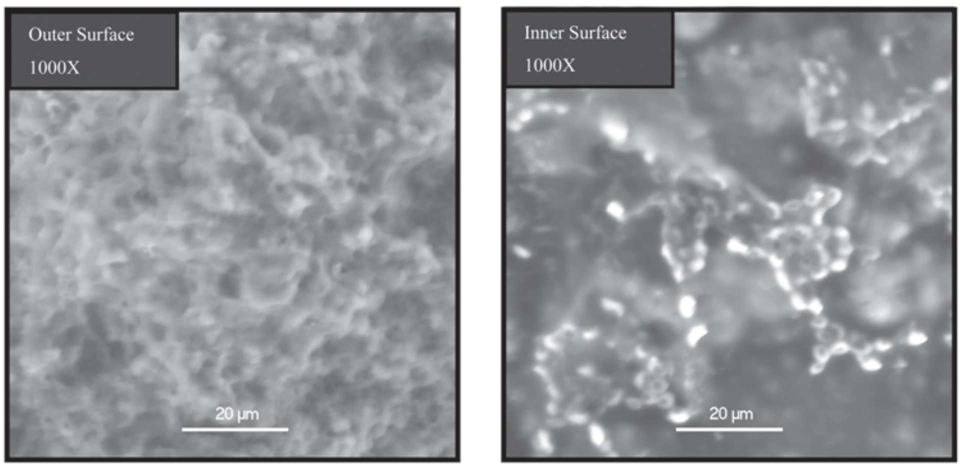

Fig. 4. ESEM visualization of outer and inner surfaces of fouling material.

Results and Discussion

Visual Observation

Visual inspection of the lamps after 48 h of operation revealed a large amount of a rubber-like fouling material surrounding the quartz tube surface (Fig. 3). Figure 4 shows ESEM visualization of the outer and inner surfaces of the fouling materials. The outer surface (the side facing the flow) of the fouling materials was creamy white while the inner surface (the side facing the lamp) was yellowish brown. Morales and van Boekel *(32)* reported that milk and milk-based systems darken when increasing the intensity of heat because of the Maillard reaction, which is a complex network of chemical reactions in which reducing sugars react with proteins or amino acids. Maillard reaction products include volatile compounds of low molecular mass, nonvolatile colored compounds of intermediate

Table 2
Some Characteristics of UV Reactors and Fouling Materials[a]

Parameter	Reactor 1	Reactor 2	Reactor 3
Flowing material thickness (mm)	18	13	6
Reactor volume (L)	1.100	0.598	0.201
Flow rate (L/h)	0.55	0.30	0.10
Steady-state outlet temperature (°C)	42.0	49.0	60.0
Cumulative cheese whey (L)	26.4	14.4	4.8
Weight of fouling material (g)	14.4187	15.3099	25.2548
Moisture content of fouling material (%)	82.4	85.3	80.9
Cumulative cheese whey fat (g)[b]	124.08	67.68	22.46
Fat content of fouling material (g/kg)[c]	21.5	23.6	28.2
Cumulative fouling material fat (g)	0.3100	0.3613	0.7122
Cumulative cheese whey protein (g)[b]	262.7539	143.3203	47.7734
Protein content of the fouling material (g/kg)[c]	108.6	121.8	132.0
Cumulative fouling material protein (g)	1.5659	1.8647	3.3336

[a]Values are presented on a wet basis.
[b]The raw cheese whey contains 0.47% fat (4700 mg/L).
[c]Obtained from the chemical analysis.

molecular mass, and brown substances of high molecular mass. Finot et al. *(33)* reported that whey is much more sensitive to the Mallard reaction than whole milk because it is rich in lactose and has soluble proteins.

Characterization of Fouling Material

Table 2 gives some of the characteristics of the UV reactors and the fouling materials, and Table 3 provides the mineral composition of the cheese whey and fouling materials.

Weight

The amount of fouling material increased with a decrease in the thickness of the flowing cheese whey. It was 14.42, 15.31, and 25.25 g for the first, second, and third UV reactors, respectively. The average moisture content of the fouling materials was 82.9 ± 2.2% with a coefficient of variation of 2.7%. The total amount of cheese whey passed through the UV reactors during the course of the study was 26.4, 14.4, and 4.8 L for the first, second, and third UV reactors, respectively. Cairns *(34)* reported that more flowing liquid volume per lamp results in more UV-absorbing organics and inorganics that could foul the lamp sleeve. However, the highest amount of fouling material was obtained with the third UV reactor, which had the smallest volume of cheese whey (4.8 L) passing through in 48 h. This was owing to the higher temperature observed in this reactor.

Sheriff and Gehr *(35)* reported that fouling is a function of time and that fouling rate is governed by several factors including the geometry of fouling surfaces, velocity, surface temperature, and liquid composition. About 50% of the input power of a typical 65-W low-pressure mercury

Table 3
Elements Present in Raw Cheese Whey and Fouling Material

Element	Cheese whey (mg/L)[a]	Cumulative cheese whey[b] Reactor 1 (mg)	Reactor 2 (mg)	Reactor 3 (mg)	Fouling material[a] Reactor 1 (mg/kg)	Reactor 2 (mg/kg)	Reactor 3 (mg/kg)	Cumulative fouling materials[c] Reactor 1 (mg)	Reactor 2 (mg)	Reactor 3 (mg)
Mg	94	2481.6	1353.6	451.2	179	205	242	2.6	3.1	6.1
Ca	429	11,325.6	6177.6	2059.2	586	776	1148	8.4	11.9	29.0
Mn	1	26.4	14.4	4.8	4	9	10	0.1	0.1	0.3
K	1670	44,088.0	24,048.0	8016.0	3300	3470	4010	47.6	53.1	101.2
Na	684	18,057.6	9849.6	3283.2	1070	1120	1680	15.4	17.1	42.4
Fe	42	1108.8	604.8	201.6	130	229	663	1.9	3.5	16.7
P	154	4065.6	2217.6	739.2	2290	2913	3240	33.0	44.6	81.8
S	483	12,751.2	6955.2	2318.4	2500	3200	5200	36.0	49.0	131.3

[a]Calculated based on 2-h residence time and 48-h operation period.
[b]Obtained from the chemical analysis.
[c]Calculated based on the basis that the total amount of fouling material obtained after 48 h of operation was 14.42, 15.31, and 25.25 g for the first, second, and third UV reactors, respectively.

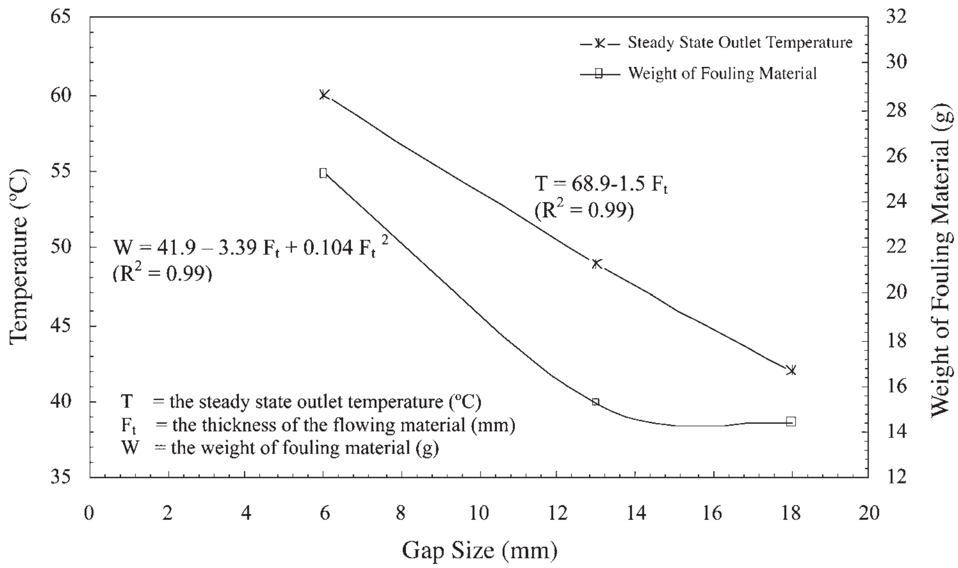

Fig. 5. Weight of fouling material and steady-state temperature as function of thickness of flowing material.

lamp is converted into UV radiation and the rest is converted into heat. Blatchley and Peel *(36)* stated that the flowing fluids in the UV systems act as a coolant, and if the fluid inûPhe sytÜ,m is too shallow lamps can overheat, causing excessive local fouling and premature deterioration of lamps.

The steady-state temperature of the UV reactor was affected by flowing material thickness. The temperature was 42, 49, and 60°C for the first, second, and third UV reactors, respectively. The results obtained from our study indicated a strong relationship between the thickness of the flowing material and the extent of lamp fouling. The thickness of the flowing material affected the temperature, which, in turn, affected the amount of accumulated fouling material (Fig. 5). The relationship between the steady-state outlet temperature and the thickness of the flowing material followed a linear expression ($R^2 = 0.99$), and the relationship between the weight of accumulated fouling material and the thickness of the flowing material followed a polynomial expression ($R^2 = 0.99$), as shown in Eqs. 1 and 2. The direct relation between the weight of the fouling material and the steady-state temperature (Fig. 6) followed a polynomial expression ($R^2 = 0.99$), as shown in Eq. 3. Therefore, the effect of temperature and flow thickness on the weight of fouling material can be described by Eq. 4.

$$T = 68.9 - 1.5F_t \qquad (6 \le F_t \le 18) \tag{1}$$

$$W = 41.9 - 3.39F_t + 0.104F_t^2 \qquad (6 \le F_t \le 18) \tag{2}$$

$$W = 97.9 - 3.80T + 0.0432T^2 \tag{3}$$

$$W = 0.593T - 2.29F_t + 0.0951F_t^2 \qquad (6 \le F_t \le 18) \tag{4}$$

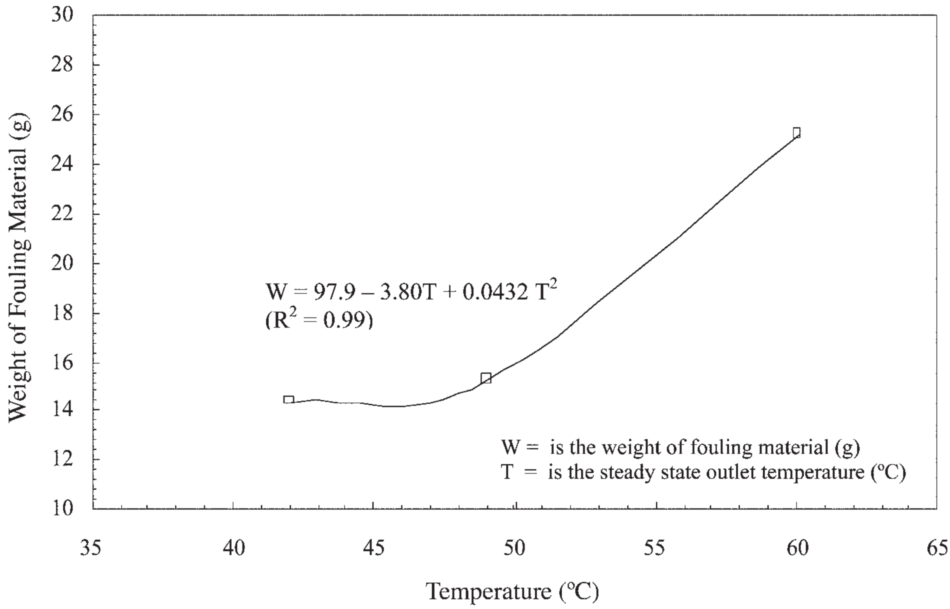

Fig. 6. Weight of fouling material as function of steady-state outlet temperature.

in which T is the steady-state cheese whey outlet temperature (°C), F_t is the thickness of the flowing material (mm), and W is the weight of the fouling material accumulated on the quartz sleeve surface (g).

Fat Content

The raw cheese whey contained about 0.47% fat, whereas the fouling materials obtained from the first, second, and third UV reactors contained about 2.15, 2.36, and 2.82% fat, respectively. Although the percentage of fat in the fouling materials increased slightly with a decrease in the thickness of the flowing material, the amount of fouling material deposited on the quartz surface increased significantly with a decrease in the thickness of the flowing material. Consequently, the total amount of fat obtained in the fouling material was 0.31, 0.36, and 0.71 g for the first, second, and third UV reactors, respectively. These amounts represented about 0.25, 0.53, and 3.17% of the total fat of 124.08, 67.68, and 22.46 g passed through the first, second, and third UV reactors during 48 h of operation, respectively.

Whey lipids are mainly phospholipids (3-*sn*-phosphatidylcholine) derived from milk fat globule membrane (MFGM) fragments that remain dispersed in a stable colloidal state *(37,38)*. The high negative surface charge density resulting from the phosphate groups of the bilayer membrane, as well as the high hydrophilicity of the membrane surface and the electrostatic repulsion between the membrane particles, is responsible for the colloidal stability of MFGM fragments in cheese whey. The relationship between phosphorous and fat contents of the fouling material (Fig. 7) can be described by the following equation ($R^2 = 0.99$):

$$F = 96.0 - 0.0605P + 0.000012P^2 \qquad (5)$$

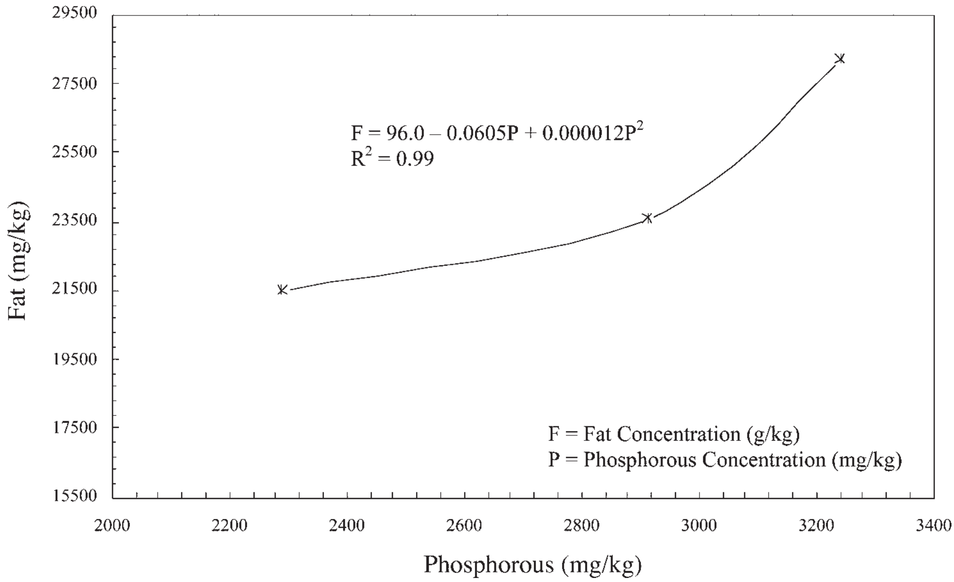

Fig. 7. Relationship between phosphorus and fat in fouling material.

in which F is the fat concentration in the fouling material (g/kg) and P is the phosphorous concentration in the fouling material (mg/kg).

Protein Content

The raw cheese whey contained about 9.95 g/L of protein, which represented about 1.0% of the raw cheese whey. The protein content of the fouling materials was about 10.9, 12.2, and 13.2% for the first, second, and third UV reactors, respectively. The percentage of protein in the fouling materials increased slightly with a decrease in the thickness of the flowing material. The total amount of protein lost from the raw cheese whey during the 48-h operating time was 0.60, 1.30, and 7.0% of the total protein passed through the first, second, and third UV reactors, respectively.

According to Savant and Torres *(39)*, whey proteins represent 20% of the total proteins found in milk and consist predominantly of β-lactoglobulin (50%), α-lactalbumin (12%), immunoglobulins (Igs) (10%), bovine serum albumin (5%), and proteose-peptones (0.23%). Cheryan *(29)* reported that proteins are a major foulant because of the multiplicity of functional groups, the charge density within the protein molecule, the varying degrees of hydrophobicity, and the complex secondary and tertiary structure that allows a protein to interact with other components and materials. This researcher indicated that calcium in ionic form acts as a bridge between the lamp surface and protein, leading to faster protein fouling.

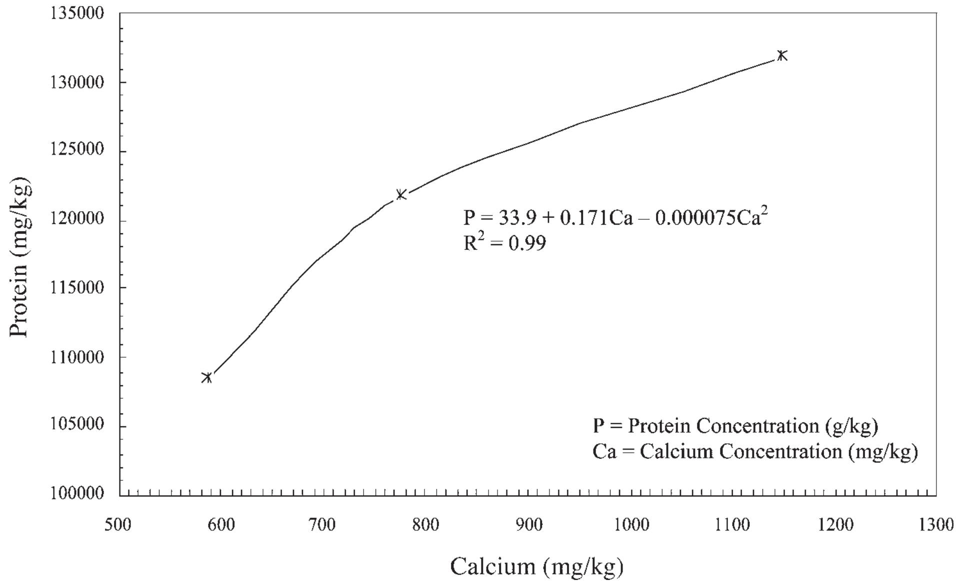

Fig. 8. Relationship between protein and calcium in fouling material.

The relationship between calcium and protein in the fouling material (Fig. 8) can be described by the following equation ($R^2 = 0.99$):

$$P = 33.9 + 0.171\mathrm{Ca} - 0.000075\mathrm{Ca}^2 \tag{6}$$

in which P is the protein concentration in the fouling material (g/kg) and Ca is the calcium concentration in the fouling material (mg/kg).

Minerals Content

The raw cheese whey contained about 0.4% minerals (94 mg/L of Mg, 429 mg/L of Ca, 1 mg/L of Mn, 1670 mg/L of K, 684 mg/L of Na, 42 mg/L of Fe, 154 mg/L of P, 483 mg/L of S, and 443 mg/L of others). Cheryan *(29)* reported that mineral salts are important foulants that can bind directly to surfaces by charge. EDX analysis (Fig. 9) revealed almost the same elemental composition (C, O, Na, Al, P, S, Cl, K, Ca, and P) for all of the fouling materials obtained from the three UV reactors. However, the total mineral content of the fouling materials was 1.02, 1.19, and 1.62% for the first, second, and third UV reactors, respectively. The fouling material obtained from the first UV reactor contained 179, 586, 4, 3300, 1070, 130, 2290, and 2500 mg/kg, that obtained from the second UV reactor contained 205, 776, 9, 3470, 1120, 229, 2913, and 3200; and that obtained from the third UV reactor contained 242, 1148, 10, 4010, 1680, 663, 3240, and 5200 mg/kg of Mg, Ca, Mn, K, Na, Fe, P, and S, respectively. The cheese whey that passed through the first, second, and third UV reactors lost about 0.10, 0.07, 0.38, 0.11, 0.09, 0.17, 0.81, and 0.28%; 0.23, 0.19, 0.69, 0.22, 0.17, 0.58, 2.01, and 0.70%; and 1.35, 1.41, 6.25, 1.26, 1.29, 8.28, 11.07, and 5.66% of the Mg, Ca, Mn, K, Na, Fe, P, and S, respectively.

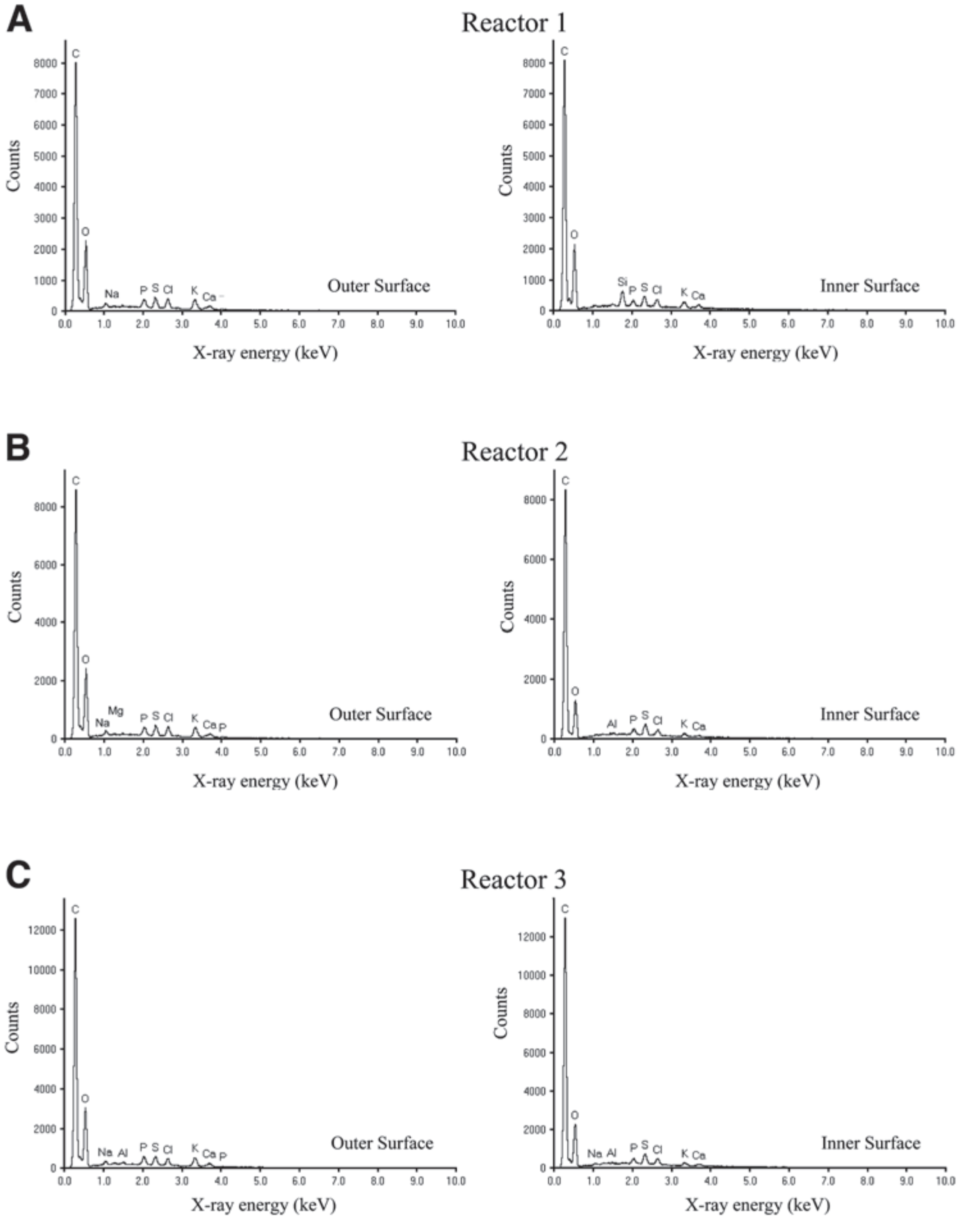

Fig. 9. Elements identified using EDX analysis: **(A)** first reactor; **(B)** second reactor; **(C)** third reactor.

Mechanism of Lamp Fouling

The fouling material was found to contain 63.51–77.19% protein, 12.57–16.49% fat, and 6.51–9.47% minerals on dry weight bases, depending on the thickness of the flowing material. The concentrations of fat, protein, and minerals in the fouling material increased with a decrease in the thickness of the flowing material, as shown in Fig. 10.

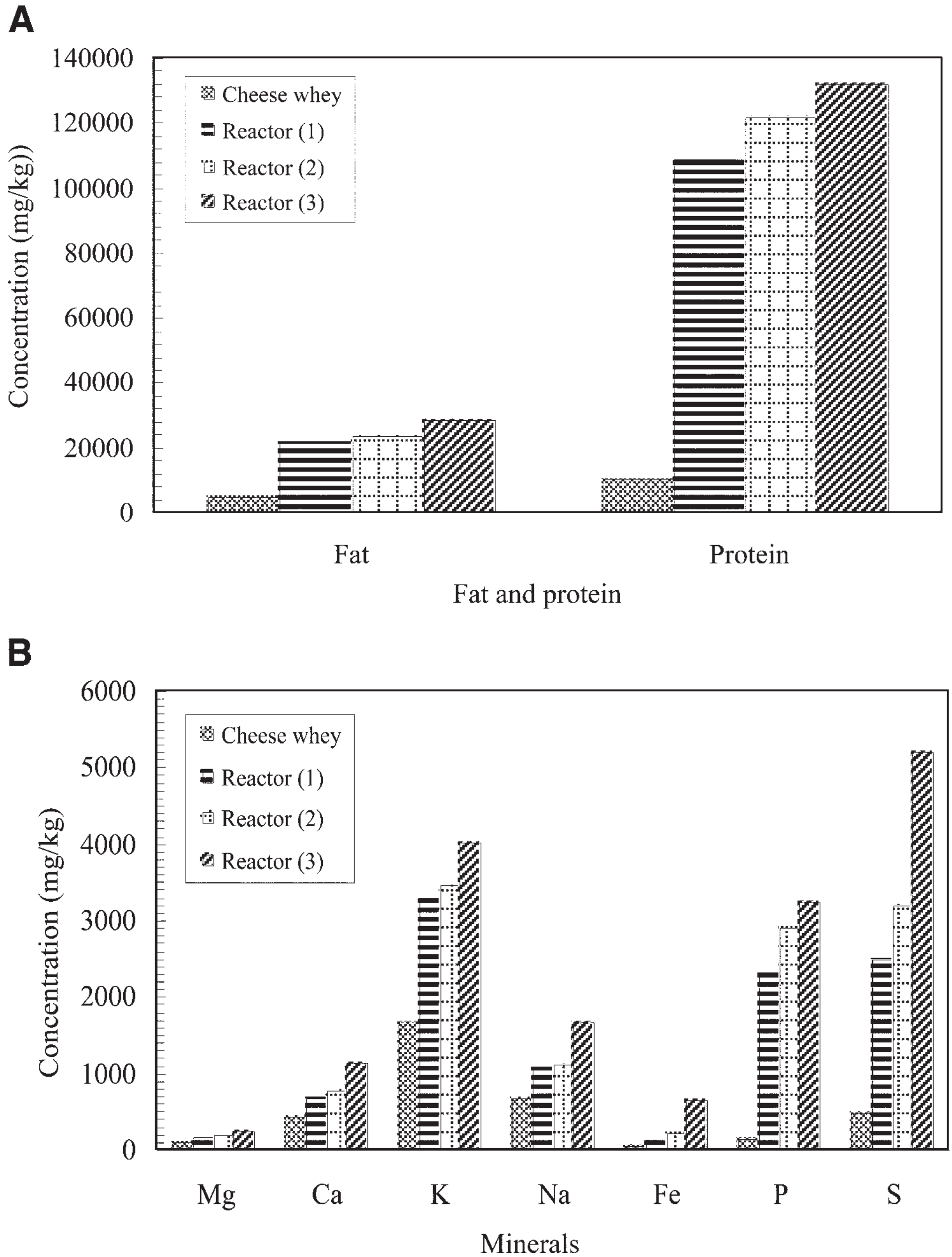

Fig. 10. **(A)** Fat, protein, and **(B)** minerals found in raw cheese whey and fouling materials.

According to Sheriff and Gehr *(35)*, the accumulation of fouling material on the quartz surface in UV reactors can be the result of direct ion exchange, thermally induced precipitation, and/or particle sedimentation. The UV reactors used in our study were tubular-type reactors with vertical flow, and precipitation owing to inverted solubility and particle sedimentation could not induce lamp fouling in this case. Thus, fouling was most likely owing to direct ion exchange. However, the high temperature and low pH attained enhanced fouling by making the constituents of the cheese whey more soluble and reactive. Quartz is a hydrophilic surface owing to the presence of amphoteric surface groups, which express a net negative surface charge at near neutral or alkaline pH. In the pH range of 5.0–5.5, Ig is positively charged *(40)*. The dissociation of silanol (≡SiOH) groups on the quartz surface is responsible for the surface charge and provides surface sites for a wide range of reactions including adsorption, complexation, and precipitation *(41)*.

Temperature also has an effect on proteins, because the adsorption of protein molecules in the temperature range of 30–60°C generally increases with an increase in temperature. Calcium is a major cause of fouling in dairy streams and decreasing the pH increases the amount of soluble calcium, which can interact and bind to negatively charged groups on the surface of interest by electrostatic or charge effects. However, the solubility of calcium phosphate decreases with an increase in temperature *(29)*.

Although several studies have been carried out on water and wastewater disinfection using UV radiation, to our knowledge, no studies have been conducted on lamp fouling during UV sterilization of cheese whey. Andreadakis et al. *(42)* attributed lamp fouling to the formation of inorganic scale with a high calcium content. Harris et al. *(27)* reported that the scale buildup on quartz sleeves in wastewater disinfection systems usually comprises calcium, magnesium, and iron. Sheriff and Gehr *(35)*, while investigating the effect of heat and/or UV radiation on inorganic fouling of a low-pressure UV lamp, found iron (III) to be one of the main inorganic constituents that cause lamp fouling and stated that the existence of phosphorus increased the fouling rate. Lin et al. *(43)* reported that the primary mechanism responsible for the inorganic fouling in wastewater disinfection systems was thermally induced precipitation of inorganic constituents and impaction of preexisting colloidal particles. The cheese whey used in the present study contained Mg, Ca, K, Na, Fe, P, and S and the concentration of these elements in the fouling material increased with decreasing gap size. The amount of the fouling material can be described as a function of the concentrations of these elements by the following equation ($R^2 = 0.99$):

$$W = 0.118\text{Ca} + 0.0854\text{Mg} + 0.065\text{Na} + 0.037\text{Fe} + 0.001\text{P} - 0.0131\text{K} - 0.0414\text{S} \quad (7)$$

in which W is the weight of fouling material accumulated on the quartz sleeve surface (g), Ca is the concentration of calcium in the fouling material (mg/kg), Mg is the concentration of magnesium in the fouling material (mg/kg), Na is the concentration of sodium in the fouling material (mg/kg), Fe is the concentration of iron in the fouling material (mg/kg), P is the concentration of phosphorous in the fouling material (mg/kg), K is the concentration of potassium in the fouling material (mg/kg), and S is the concentration of sulfur in the fouling material (mg/kg).

High correlations between the weight of the fouling material and the concentration of each of Ca, Mg, Na, Fe, P, K, and S were also obtained. Although positive relationships between the weight of the fouling material and the concentration of each of K and S were realized, the negative sign in Eq. 6 may indicate that these elements might interfere with the accumulation of other elements, thus reducing the net weight of fouling material. This phenomenon is worth investigating.

Conclusion

The present study revealed a high susceptibility of lamp fouling during on-line sterilization of cheese whey using tubular-type UV reactors. Fouling material completely surrounded the quartz sleeve surface, causing limited performance. There were strong relationships among the thickness of the flowing material, temperature, and amount of fouling material accumulated on the surface of the quartz sleeve. Decreasing the thickness of the flowing material increased the outlet temperature of the cheese whey and increased the amount of fouling material. The amount of fouling material obtained was 14.42, 15.31, and 25.25 g and the cheese whey outlet temperature (at steady state) attained was 42, 49, and 60°C for the first, second, and third UV reactors, respectively. The fouling material had a moisture content of 82.9 ± 2.2% and contained 63.51–77.19% protein, 12.57–16.49% fat, and 6.51–9.47% minerals on dry bases compared with 93% moisture, 1% protein, 0.5% fat, and 0.4% minerals (Mg, Ca, Mn, K, Na, Fe, P, and S) in the cheese whey. The concentrations of fat, protein, and minerals in the fouling material increased with a decrease in the flow thickness. Fat and protein concentrations in the fouling material increased with an increase of phosphorus and calcium, respectively. Adsorption and direct ion exchange were the most likely fouling mechanisms. However, the extent of fouling was enhanced by the high temperature and the low pH attained in the study. To use UV radiation for on-line sterilization of cheese whey effectively, a new design in which the flowing cheese whey is separated from the lamp should be developed.

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