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Effect of Flow Characteristics on Online Sterilization of Cheese Whey in UV Reactors

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Abstract An ultraviolet (UV) coil reactor was designed and used for the online sterilization of cheese whey. Its microbial destruction efficiency was compared to that of the conventionally used UV reactor. Both reactors have the same geometry (840 ml volume and 17 mm gap size) and were tested at 11 flow rates of 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, and 70 ml/min. The results obtained from this study showed that despite of its high turbidity, cheese whey could be sterilized using UV radiation if the proper reactor design and flow rate are used. The performances of the UV reactors were governed by the flow rate and the hydraulics of flow inside the reactor. The flow was laminar in both the reactors, as the Reynolds number was in the range of 1.39–20.10. The phenomenon of Dean Flow was observed in the coil reactor and the Dean number was in the range of 1.09–15.41. Dean vortices resulted in higher microbial destruction efficiency in the coil reactor in a shorter retention time. The rate of microbial destruction was found to be exponential in the conventional reactor and polynomial in the coil reactor. Increasing the flow rate from 5 ml/min to 70 ml/min decreased the microbial destruction efficiency of the conventional reactor from 99.40 to 31.58%, while the microbial destruction efficiency in the coil reactor increased from 60.77% at the flow rate of 5 ml/min to 99.98% at the flow rate of 30 ml/min and then decreased with further increases in flow rate reaching 46.2% at the flow rate of 70 ml/min. The maximum effluent temperatures in the conventional and coil reactors were 45.8 and 46.1°C, respectively. Fouling in the coil reactor was significantly less compared to the conventional reactor. The extent of fouling was influenced by flow rate and reactor's hydraulics.

Keywords Cheese whey · Sterilization · Ultraviolet radiation · Flow rate

Introduction

Cheese whey is a greenish-yellow watery by-product of cheese making process. The composition of cheese whey is about 93% water, 5% lactose, 0.9% protein, 0.3% fat, 0.2%

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lactic acid, and small amounts of vitamins [1]. Due to its high biochemical oxygen demand (40–60 g/l), cheese whey disposal has created major problems for the dairy industry [2–5].

Cheese whey is considered a low-cost carbon source for fermentation processes and is available all year around. It has been used for producing value added products such as animal feed [6], whey powder [7], whey protein concentrates [8], lactose [9], whey beverages [10], single-cell protein [11, 12], ethanol [4], methane [13], fertilizers [7, 14], organic acids [15], icers and anti-icers [16, 17], and biodegradable plastics [18]. Using cheese whey in production of these value added products not only minimize the problems associated with its disposal, but also improves the economics of dairy industry.

However, to use cheese whey in fermentation systems for the production of value added products for animal and human consumption, sufficient treatment to kill the present undesirable microorganisms must be provided. Although pasteurization has been used to sterilize cheese whey, the process is very time consuming [19]. To save time while ensuring complete destruction of microorganisms, continuous sterilization technique for cheese whey using ultraviolet-C (UV-C) radiations has been suggested by Mahmoud and Ghaly [5]. UV light in the spectrum of 180–320 nm has the germicidal effect with its optimum at 265 nm [20]. Because of its germicidal effect, the UV radiation has been extensively used in many applications such as drinking water disinfection [21], medical devices sterilization [22], air disinfection [23], and juice pasteurization [24]. However, conventional UV reactors in which the flow is laminar produces significant amount of heat that causes fouling. To create mixing while maintaining a low flow rate (long retention time), Dean flow has been suggested. The phenomenon of Dean flow refers to a secondary flow caused by flow movement in curved tubes [25]. The secondary flow is the double spiral motion produced by a gradual bend in a closed passage (bend pipe or curved pipe). The direction of the secondary flow is perpendicular to the main direction of flow. Dean vortices resulting from flow in helical tubes are known as an effective means of heat and mass transfer enhancement [26] and have been used to reduce concentration polarization and membrane fouling during nano-filtration [27].

Objectives

The objectives of this study were: (a) to design a photoreactor in which the material moves according to Dean flow to allow for effective online sterilization of cheese whey in a short retention time, and (b) to compare the efficiency of this photoreactor with that of a conventional reactor at various flow rates.

Experimental Apparatus

The experimental set up (Fig. 1) consisted of UV reactors, cheese whey feeding, and effluent removal system and a data logger.

UV Reactors

Two 380-mm arc length low pressure mercury lamps each enclosed in a 21-mm diameter (OD) quartz tube were used in two UV reactors. The inner and the outer diameter of both reactors were 55 and 61 mm. A 3-mm thick stainless steel chamber gave a gap size (distance between the quartz sleeve and the inner surface of reactor casing) of 17 mm in

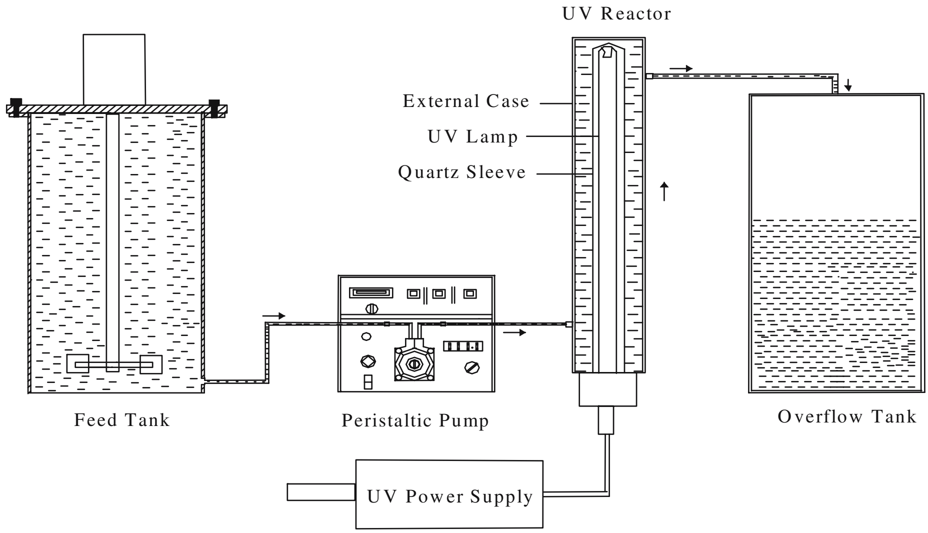


Fig. 1 Experimental setup

both reactors. A coil made of stainless steel, with a length of 448 mm, a thickness of 0.85 mm, and a pitch of 20 mm, was used to create Dean flow in one of the reactors. The outlet of the coil reactor was 13.4 mm above the outlet of the conventional reactor to compensate for the volume occupied by the coil and thus give the same working volume of 840 ml in both reactors. Figure 2 shows the geometry of the two UV reactors.

Whey Feeding and Effluent Removal System

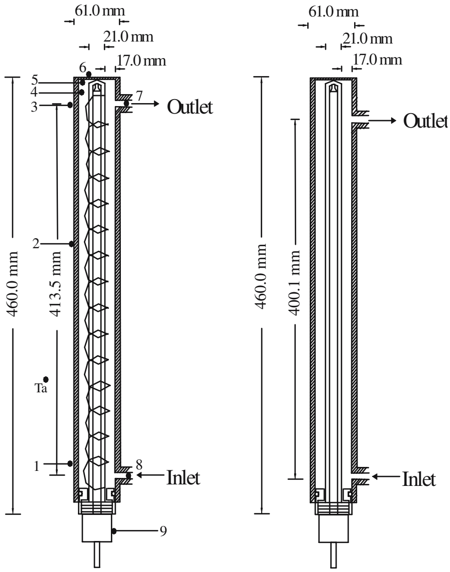
The feeding and effluent removal system consisted of a feeding tank, feeding pumps and an effluent collection tank. The feeding tank (11 l) was made of a Plexiglas cylinder of 4 mm wall thickness, 200 mm ID, and 435 mm height. The bottom and cover of the feeding tank were made of 4 mm thick lexiglas circular plates. A mixing shaft having stirring paddles (1.5 mm thick and 72 mm in length) of 9 mm diameter and a 370.5-mm length was installed through the center of the feeding tank cover and driven by an electric motor (Model 5935932, Type NSI-10RS3, Bodine Electric Company, Chicago, USA) mounted on top of the feeding tank cover. The outlet port (4 mm diameter) of the feeding tank was located at 15 mm from the bottom. Two variable speed peristaltic pumps and Masterflex precision tubing (Digi-Staltic, Masterflex model 7253-60, head model 77200-50, tubing no. EL-06429-14, Barnant Company, Division of Cole Parmer Instrument, Co., Barrington, IL.) were used to pump the material from the feeding tank into the UV reactors. A 10-l effluent collection tank was made from 4 mm thick Plexiglas cylinder of 200 mm ID and 390 mm height. The cover and the bottom of the overflow tank were made from 4 mm thick Plexiglas plates of 210 mm diameter.

Data Logger

A Digital datalogger (Model 4702-5 E, Cole Parmer, Chicago, Illinois) was used to record the temperature changes in the reactors. The temperature was measured using type T

Ta. Laboratory air temperature

1. Temperature on the outside surface of the reactor opposite to inlet
2. Temperature on the outside surface of the reactor at the mid height
3. Temperature on the outside surface of the reactor opposite to outlet
4. The temperature of the reactor head space
5. The Inside surface temperature of the reactor top
6. The temperarture on the outside surface of the reactor top
7. The oulet cheese whey temperature
8. The inlet cheese whey temperature
9. The temperature of the lamp socket surface



a Newly designed coil reactor b Conventional reactor

Fig. 2 UV reactors

thermocouples at nine different locations as shown in Fig. 2: (a) the outside surface of the reactor opposite to inlet, (b) the outside surface of the reactor at the mid-height, (c) the outside surface of the reactor opposite to outlet, (d) the reactor head space, (e) the inside surface of the reactor top, (f) the outside surface of the reactor top, (g) the outlet, (h) the inlet, and (i) the lamp socket surface.

Experimental Procedure

Cheese Whey Collection and Preparation

The cheese whey used in the study was obtained from the Farmer's Cooperative Dairy Plant in Truro, Nova Scotia. Sufficient amount of cheese whey was collected in several containers and stored in the Biotechnology Laboratory at about −25°C until needed. When required for use, a few containers were withdrawn from the freezer and kept at room temperature to thaw and to increase the microbial population. Some characteristics of the cheese whey are presented in Table 1.

Experimental Protocol

The performance of the two reactors were evaluated at 11 flow rates (5, 10, 15, 20, 25, 30, 35, 40, 50, 60, and 70 ml/min) which gave retention times of 168, 84, 56, 42, 33.6, 28, 24, 21, 16.8, 14, and 12 min, respectively. Before starting each experimental run, the UV reactors and all accessories (feeding tank, overflow tank, and tubings) were all cleaned with detergent and hot water, and then, chemically sterilized using 2% sodium metabisulfite solution to eliminate any microbial contamination. The cheese whey was pumped through

Table 1 Some characteristics of the cheese whey.

Characteristics	Measured value	Units
Total solids (TS)	56,800	mg/l
Volatile solids (VS)	47,900	mg/l
VS as percent of TS	84.33	%
Ash	8,900	mg/l
Ash as prevent of TS	15.67	%
Total chemical oxygen demand (TCOD)	75,800	mg/l
Soluble chemical oxygen demand (SCOD)	58,000	mg/l
SCOD as percent of TCOD	76.52	%
Total Kjeldahl nitrogen (TKN)	1,500	mg/l
Ammonium nitrogen (AN)	270	mg/l
AN as percent of TKN	18	%

the UV reactors at the required flow rates using the peristaltic pumps. The temperature readings were recorded at the different flow rates. Samples were collected from the inlet and the outlet for the plate count analysis.

Analysis

Microbial counts were performed on untreated and UV treated cheese whey samples. A plate count agar (DIFCO, 0751-17-2), which contained 5 g of bacto yeast agar dissolved in 1 l and sterilized at 121°C and 101.4 kPa for 15 min in an autoclave (model STM-E, Market Forge Sterilmatic, New York, NY), was poured into several Petri dishes. Serial dilutions of 10^{-1}–10^{-7} were prepared from the samples. An aliquot of 0.1 ml of each of the dilutions was placed on the plate count agar in the petri dish (in triplicate) and gently swirled until consistently spread on the agar surface with the glass spreader. The Petri dishes were incubated at 32°C in an incubator (Fisher Isotemp*, Cat. No. 11-680-626, Fisher Scientific, Whitby, Ontario, Canada) until visible growth was observed. The visible growth of colonies was counted as colony-forming units per millimeter (CFU/ml) according to the procedure described in the Standard Methods for the Examination of Dairy Products [28].

Results and Discussion

Microbial Survival

The cheese whey had an initial microbial population of 7.6×10^{6} cells/ml. The final microbial populations in the effluent of the conventional and coil reactors operating at various flow rates are shown in the Table 2. The results are the average of the three replicates. The coefficient of variation varied from 0.0 to 9.3%. The survival curves for both reactors are shown in Fig. 3.

Survival curves, which are commonly used to interpret the inactivation kinetics of microorganism, are semilog plots of the ratio of the concentrations of the final number of organisms found after UV treatment (N) to the initial number of microorganisms (N_o) vs residence time. The results obtained from the conventional reactor showed that the UV radiations are capable of reducing the microbial population in the cheese whey by 31.6–

Table 2 Effect of flow rate on final cell number and destruction efficiencies of the single conventional and coil reactors.

Flow rate (ml/min)	Residence time (min)	Conventional reactor		Coil reactor	
		Final cell number ($\times 10^6$)	Destruction efficiency (%)	Final cell number ($\times 10^6$)	Destruction efficiency (%)
5	168.0	0.046	99.40	2.903	60.77
10	84.0	0.122	98.40	2.314	69.52
15	56.0	0.236	96.90	1.096	85.56
20	42.0	0.547	92.80	0.285	96.24
25	33.6	1.003	86.80	0.125	98.35
30	28.0	1.718	77.40	0.002	99.98
35	24.0	2.364	68.90	0.008	90.90
40	21.0	3.010	60.40	0.437	75.80
50	16.8	4.028	47.00	1.830	53.51
60	14.0	4.669	38.56	3.800	50.20
70	12.0	5.200	31.58	4.080	46.20

Initial cell number is 7.6×10^6 (cells/ml)

99.4% (reducing N/N_o from 0.684 to 0.006), depending on the flow rate, the lower the flow rate, the higher microbial destruction. Low flow rates resulted in longer retention time, thus, increasing the possibility of the scattered UV radiation hitting the microbial cells and causing germicidal effect. Darby et al. [29] stated that as with chemical disinfection, the liquid medium must have sufficient contact time with the UV light. With increases in flow rates, fewer microorganisms were exposed to UV in the conventional reactor. The

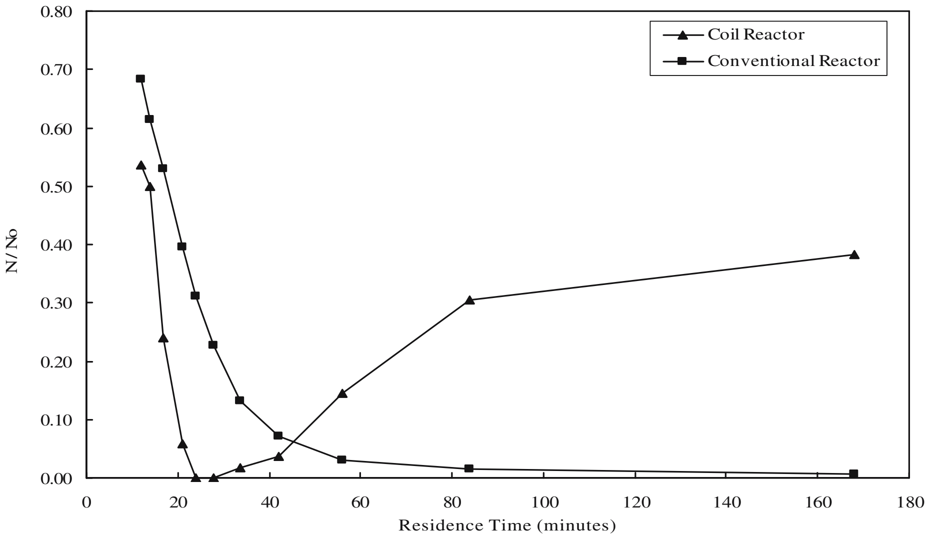


Fig. 3 Survival curves for the coil and conventional reactors

relationship between the survival ratio (N/N_o) and the residence time (t) for the conventional reactor (Fig. 3) can be best described by the following exponential equation.

$$\frac{N}{N_o} = e^{-0.0319t} \quad R^2 = 0.83 \tag{1}$$

where:

N is the final number of cells (cells/ml)
N_o is the initial number of cells (cells/ml)
t is the residence time (min)

Based on these above equation, it would require more than 496 min (1.69 ml/min) to destroy the whole initial population in cheese whey in the conventional reactor. Koch [30] and Mitscherlich and Marth [31] reported that microorganisms exposed to ultraviolet germicidal irradiation (UVGI) experience an exponential decrease in population similar to other methods of disinfection such as heating, ozonation, and exposure to ionizing radiation. Mahmoud and Ghaly [5] found that the destruction of microbial cells present in the cheese whey in conventional UV reactors could be described by first-order equation. The relationship between the survival ratio (N/N_o) and the residence time of the coil reactor showed a different trend from that of the conventional reactor. At low flow rates, there was no mixing taking place, and the coil shielded the microorganism from being exposed to UV, thereby, resulting in less microbial destruction. With increases in the flow rate, microbial destruction increased as a result of mixing and increased exposure of microorganism to UV due to the development of secondary flows caused by the presence of helical vortices (Dean vortices). The relationship between the survival ratio (N/N_o) and the residence time (t) for the coil reactor was found to be best described by the following polynomial equation:

$$\frac{N}{N_o} = 2.137 - 0.196t + 0.0065t^2 - 0.0001t^3 + 8E - 07t^4 - 3E - 09t^5 + 6E - 12t^6 \tag{2}$$

Based on the above equation, the optimum residence time would be 28 min (30 ml/min).

Destruction Efficiency

The destruction efficiencies of the conventional and coil reactors are shown in Fig. 4. The destruction efficiency of the conventional reactor followed a decreasing trend with increases in the flow rate. It decreased from 99.40% at the flow rate of 5 ml/min (168 min residence time) to 31.58% at the flow rate of 70 mL/min (12 min residence time). The destruction efficiency of the coil reactor increased from 60.77% at the flow rate of 5 ml/min (168 min residence time) to 99.98% at the flow rate of 30 ml/min (residence time of 28 min) and then decreased with increases in the flow rate reaching 46.2% at the flow rate of 70 ml/min (12 min residence time). Flow rates above 30 ml/min resulted in shorter residence times that were insufficient for microbial destruction. Destruction efficiency, 100%, could not be achieved in either reactor.

Rajala et al. [32] reported a disinfection efficiency of 99.9% at 140 J/cm^2 in the pilot UV reactor used for wastewater treatment. Wright et al. [33], while using a thin film ultraviolet reactor to treat inoculated unpasteurized apple cider (a mixture of five strains of *Escherichia coli* O157: H7) at various flow rates (1.0–6.5 l/min) and dosage (610–94 J/m^2), reported a disinfection efficiency of 99.98%. Harrington and Hills [34] obtained a disinfection efficiency of 99.78% with a good quality shelf life during 35 days at 2.2°C. Beltran and

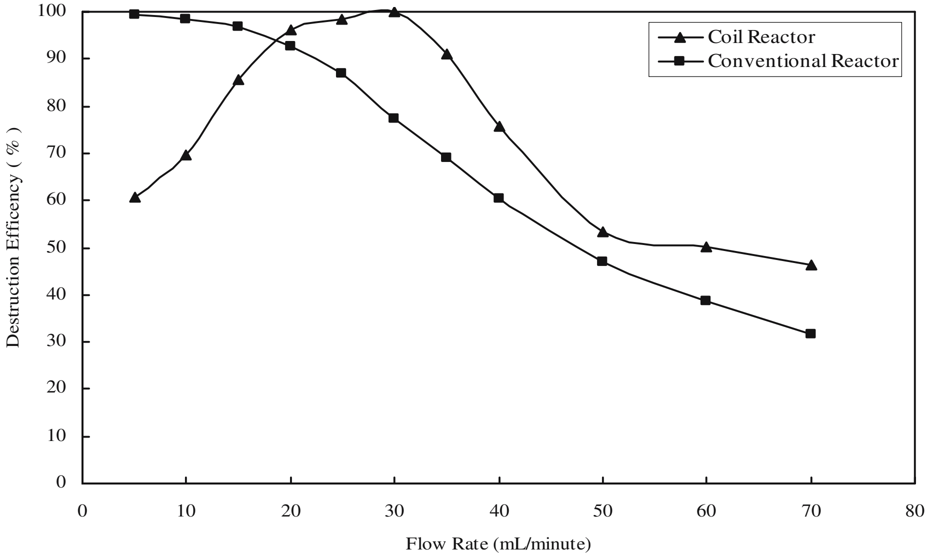


Fig. 4 Effect of flow rate on destruction efficiencies of the conventional and coil reactors

Canovas [35] reported a disinfection efficiency of 89.78–97.97% for *Saccharomyces cerevisiae*, 98.87–99.99% for *Listeria innocua*, and 99.98–99.99% for *E. coli*, while using UV reactor for treating apple juice.

According to USEPA [36], choosing a UV disinfection system depends on three critical factors: (a) characteristics of the liquid medium, (b) UV intensity, and (c) hydraulic properties of the reactor. Mahmoud and Ghaly [5] found that cheese whey is a highly turbid waste material having a very poor transmittance to UV radiation in the germicidal range, and most of this radiation in this range was either absorbed or scattered, rather than being transmitted through the cheese whey medium as a result of its high turbidity (4,317 NTU), high suspended particles (36.81%), and large solid particles (~20% >100 μm). Meulemans [20] stated that the effective tolerance of the various types of microorganisms to UV radiation varies considerably from small doses for bacteria to very large doses for algae. Darby et al. [29] stated that radial turbulence (perpendicular to the flow path) produces adequate mixing in the nonuniform UV intensity field in the reactor which reduces the effect of particle shading on UV light emitted by the lamps. Koutchma et al. [37] used turbulent flow UV reactors to achieve 99.999% disinfection efficiency of juice products and found that higher flow rates resulted in increased disinfection efficiency in the UV reactors.

Flow Characteristics

Generally, the flow is laminar when the Reynolds number is less than 4,000 and is turbulent when it is greater than 4,000 [38]. Reynolds number calculations were performed on conventional and coil reactors using the following equations:

$$Re = Ud_{\mathrm{h}}/\nu \tag{3}$$

$$U = q/A_{\mathrm{c}} \tag{4}$$

$$d_{\mathrm{h}} = D_{\mathrm{o}} - D_{\mathrm{i}} \tag{5}$$

where:

A_c is the annular section area (m^2)
d_h is the hydraulic diameter (m)
D_i is the inner diameter (m)
D_o is the outer diameter (m)
q is the volumetric flow rate (ml/min)
U is the mean velocity (m/s)
ν is the fluid kinematic viscosity (m^2/s)

The results (Table 3) showed that the Reynolds number was 1.39 for the lowest flow rate of 5 ml/min and 20.10 for the highest flow rate of 70 ml/min, indicating that the flow was laminar in both reactors.

Ujhidy et al. [39] stated that during the laminar flow of liquid in a coil, a secondary flow is induced in a channel between the tube wall and the surface of a helical element. These counter-rotating flow patterns are maintained until dissipated downstream by viscous friction. Yang and Chang [40] and Patankar et al. [41] distinguished three regions during laminar flow in coiled tubes: (a) the region of small Dean (D_e) number (lower than 20), where the inertia forces due to the secondary flow can be neglected, (b) the region of intermediate D_e number (from 20 to 100), where the inertia forces due to secondary low balance the viscous forces and (c) the region of high D_e number (higher than 100), where the viscous forces only in the boundary layer near the tube wall are still significant. According to Nemeth and Buscky [42], the secondary flow being an orderly process does not dissipate as much energy through pressure drop as does turbulence for the same degree of inhibition of axial dispersion.

Dean number has been used as a measure of the magnitude of the secondary flow. Dean number, which is a combination of the Reynolds number and the nondimensional ratio of tube radius to radius of curvature, is a measure of geometric average of inertial and centrifugal forces to the viscous forces and can be calculated from the following equation [42].

$$D_e = R_e(r^x/\Gamma)^{0.5} \tag{6}$$

Table 3 Effect of flow rate on Reynolds number and Dean number for the conventional and coil reactor.

Flow rate (ml/min)	Residence time R_t (min)	Reynolds number R_e	Dean number D_e*
5	168.00	1.39	1.09
10	84.00	2.79	2.23
15	56.00	4.18	3.34
20	42.00	5.58	4.46
25	33.60	6.97	5.57
30	28.00	8.37	6.69
35	24.00	9.70	7.76
40	21.00	11.16	8.93
50	16.80	13.95	11.16
60	14.00	16.75	13.40
70	12.00	20.10	15.41

*Coil reactor

$$r^x = \frac{a}{2}\sqrt{\frac{1}{2} - \frac{2\delta}{a\pi}} \tag{7}$$

$$\Gamma = \left(r^2 + b^2\right)/r \tag{8}$$

$$b = h/2\pi \tag{9}$$

where:

- a is the tube diameter (m)
- b is a parameter, equal to $h/2\pi$ (m)
- D_e is the Dean number (−)
- h is the pitch of the screw line (m)
- r is the tube radius (m)
- r^x is the radius of the circle having the same surface as the area of the half cross-section beside the static element (m)

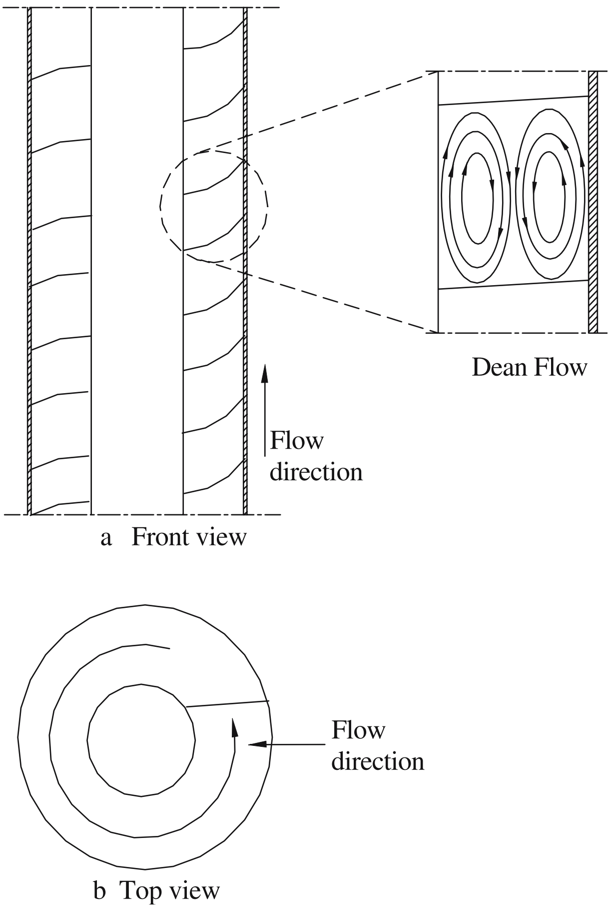


Fig. 5 Development of secondary flow in coil reactor

Table 4 Steady state temperatures at different locations in the conventional and coil reactors (°C).

Flow rate (ml/min)	Location of thermocouples																	
	1		2		3		4		5		6		7		8		9	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
5	30.8	32.9	38.5	42.4	46.1	49.2	43.2	46.2	42.2	46.4	43.1	45.5	45.8	46.1	22.2	24.3	26.9	27.4
10	24.8	27.2	35.5	36.3	41.2	42.4	36.9	40.0	37.8	41.1	39.9	39.1	40.5	41.8	22.0	23.1	25.9	25.9
15	24.8	26.5	32.4	33.4	37.2	38.6	34.3	36.8	35.4	36.9	36.9	36.7	36.8	38.0	22.8	22.8	26.0	25.4
20	24.8	24.8	29.5	30.9	33.0	35.2	30.5	33.4	31.1	34.4	33.9	32.8	34.1	35.0	22.2	23.0	26.4	25.4
25	24.7	24.5	28.8	30.7	31.8	34.2	29.1	32.4	30.5	33.4	32.6	30.4	33.8	34.8	23.1	23.6	27.0	25.7
30	24.6	24.2	28.1	30.2	31.4	33.2	28.3	31.1	29.4	32.8	31.5	30.0	32.8	33.3	24.0	23.6	27.6	25.7
35	24.2	24.7	26.8	27.4	31.0	30.4	27.2	30.3	29.1	30.4	30.3	30.1	30.2	30.8	24.0	23.4	26.8	25.9
40	24.2	24.1	24.8	25.3	30.8	29.1	27.0	28.6	28.5	28.8	29.0	28.4	28.6	29.1	24.0	23.5	26.8	25.9
50	23.5	23.9	23.9	25.0	28.5	28.7	26.4	28.1	28.1	28.0	28.4	27.5	28.1	28.8	23.4	23.4	26.8	25.9
60	23.0	23.1	23.1	24.5	26.8	26.8	26.0	27.4	27.5	27.6	27.0	26.9	27.0	27.4	23.0	22.9	26.8	25.9
70	22.6	22.4	22.8	23.8	25.0	25.7	25.2	26.1	26.4	26.5	26.4	26.5	25.5	26.2	23.6	24.0	26.8	25.9

A is the Conventional Reactor

B is the Coil Reactor

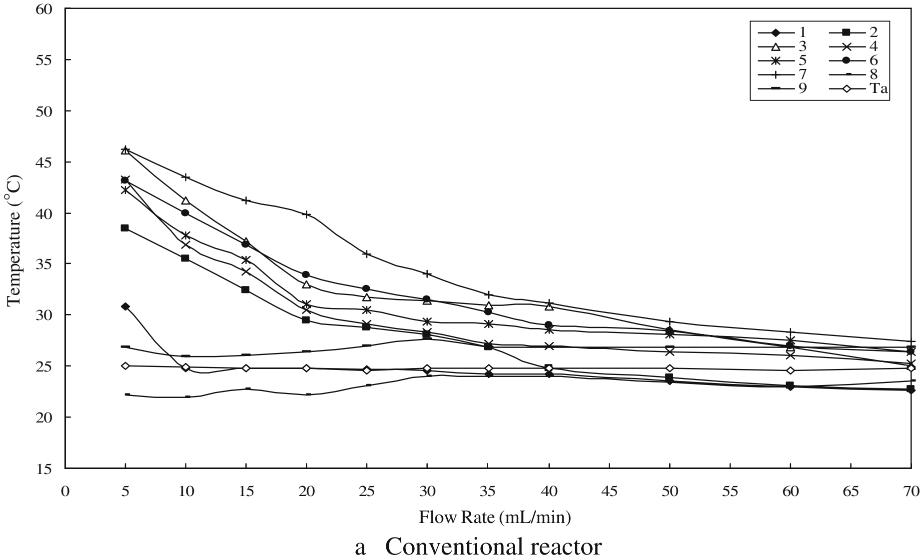
R_e is the Reynolds number (−)
Γ is the radius of curvature of the spherical line cut out by the helical element from the tubular housing (m)
δ is thickness of coil (m)
π is a constant (3.1415)

It has been found that in coiled tubes with helical elements of *L*/*d* between 1.0 and 1.5 and Reynolds number between 20 and 50, a secondary flow is expected to develop if the critical Dean number is larger than 11.6–20 [39]. Using Equations (6) to (9), the critical Dean number for the coil reactor was found to be 1.09 at 5 ml/min and 15.41 at 70 ml/min (Table 3). The *L*/*d* was found to be 1.01. These results indicated the existence of secondary flows due to helical nature of the flow as illustrated in Fig. 5. Webster and Humphrey [43] stated that the two counter-rotating vortices (Dean vortices) will be present in helical pipes, even for the most mildly curved pipe. The secondary flow started to develop in the coil reactor of Reynolds number value of less than 20. The results also indicated that as the flow rate increased, the magnitude of secondary flow increased resulting in increases of critical Dean number.

Temperature

Table 4 shows the measured values of temperatures at the steady state as affected by the flow rate in the conventional and coil reactors. Figure 6 show the variation of steady state temperature with flow rate in the conventional and coil reactors. The results indicated that there were increases in the temperature at all locations in the reactors (except the inlet temperature) until the reactors were filled up. The temperatures at all locations in the conventional and coil reactors decreased with the increase in flow rate, except for the influent temperature (location 8), which remained constant. At the steady state, the temperatures measured close to the bottom of the reactors were less than the temperatures measured at the top. This was because the liquid (which was kept at room temperature) entered the reactor at the bottom and picked up heat from the lamp as it traveled upward to the outlet. It was also noticed that the temperatures measured at all the locations in the coil reactor were slightly higher than those measured at similar locations in the conventional reactor. This could be due to the presence of coil, which releases some of heat it absorbed during the start-up period (filling period) to the moving fluid and/or the mixing created by Dean vortices. The steady state effluent temperature (location 7) decreased from 45.8°C at 5 ml/min to 25.5°C at 70 ml/min in the conventional reactor and from 46.1°C at 5 ml/min to 26.2°C at 70 ml/min in the coil reactor.

The outlet temperature reported in the literature for various UV reactors varied from 10°C to 62.8°C. Koutchma et al. [37] found that the outlet temperature of cider passing through the conventional UV reactor remained at 20–22°C. Tran and Farid [44] reported a temperature of 25°C during the ultraviolet sterilization of orange juice using conventional reactor. Mahmoud and Ghaly [5] reported cheese whey outlet temperatures of 44.5, 53.4, and 62.8°C for conventional UV reactors having gap sizes of 18, 13, and 6 mm, respectively. Abu-ghararah [45] reported a temperature range of 10–45°C during the disinfection of fecal coliform using conventional UV reactor operating at different liquid flow rates. According to environmental technology verification program conducted by USEPA [41] on UV reactors produced by Trojan Technologies Incorporated (Canada), the temperature of the effluent will vary depending on the flow rate and the reactor geometry.



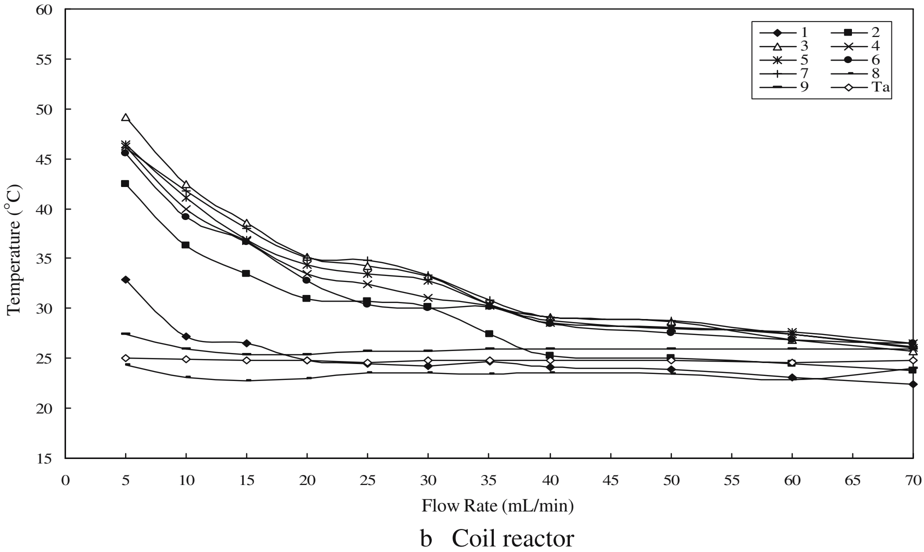
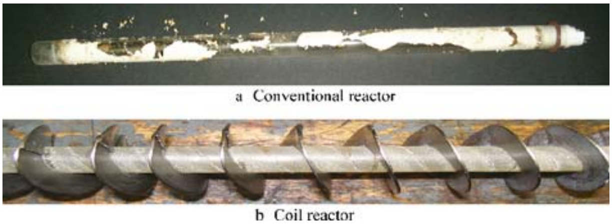


Fig. 6 Effect of flow rate on the steady-state temperatures

Fig. 7 Photograph showing fouling on UV lamps of the conventional and coil reactors



Fouling

Visual observation of the UV lamps revealed less fouling in the coil reactor compared to conventional reactor (Fig. 7). At a given flow rate, the flow through a helical coil is uniquely different from that through a straight pipe due to the secondary motion induced by an imbalance between the cross stream pressure gradient and the centrifugal force [43]. Thus, as a result of secondary flow in coil reactor, the hydraulics of the flow differed from that in the conventional reactor and resulted in less fouling. At low flow rates in the coil reactor, even though the residence time was longer, the high levels of suspended solids resulted in deposition of particles on the surface of the UV lamp, thus, blocking the exposure of microorganism to UV in the reactor after extended operation. Suspended particles and high turbidity of the liquid medium have been found to reduce the penetration ability of the UV light, and thus, reduce the efficiency of the UV conventional reactor [5]. Similarly, microorganisms can aggregate or clump together, forming particles that potentially protect microorganisms within aggregates that would otherwise be inactivated [36].

Conclusion

The results obtained from this study showed that despite of its high turbidity, cheese whey can be sterilized using UV radiation if the proper reactor design and flow rate are used. The performances of the UV reactors were governed by the flow rate and the hydraulics of flow inside the reactor. The flow was laminar in the conventional and coil reactors (Reynolds number was in the range of 1.39–20.10). The phenomenon of Dean Flow was observed in the coil reactor and the Dean number was in the range of 1.09–15.41. Dean vortices resulted in higher microbial destruction efficiency in the coil reactor in a shorter retention time compared to the conventional reactor. The rate of microbial destruction was found to be exponential in conventional reactor and polynomial in coil reactor. Increasing the flow rate from 5 to 70 ml/min decreased the microbial destruction efficiency of the conventional reactor from 99.40 to 31.58%, while the microbial destruction efficiency in the coil reactor increased from 60.77% at the flow rate of 5 ml/min to 99.98% at the flow rate of 30 ml/min and then decreased with further increases in flow rate reaching 46.2% at the flow rate of 70 ml/min. The maximum effluent temperatures in the conventional and coil reactors were 45.8 and 46.1°C, respectively. Fouling in the coil reactor was significantly less compared to the conventional reactor. The extent of fouling was influenced by flow rate and reactor's hydraulics.

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References

1. Ben-Hassan, R. M., Ghaly, A. E., & Ben-Abdallah, N. (1993). Heat generation during batch and continuous production of single cell protein from cheese whey. *Biomass and Bioenergy, 4*(3), 213–225.
2. Marshall, K. R., & Harper, W. J. (1984). Treatment of wastes from the dairy industry. In D. Barnes, C. F. Forster, & S. E. Hrudey (Ed.), *Surveys in industrial wastewater treatment, vol. 1* (pp. 296–376). Boston, MA, USA: Pitman Advanced Publishing Program.
3. Singh, R. K., & Ghaly, A. E. (1988). Cheese whey processing alternatives. ASAE Paper NO.88-6540, St. Joseph, MI.

4. Ghaly, A. E., & El-Taweel, A. A. (1994). Kinetics of batch production of ethanol from cheese whey. *Biomass and Bioenergy, 6*(6), 465–478.
5. Mahmoud, N. S., & Ghaly, A. E. (2004). On-line sterilization of cheese whey using ultraviolet radiations. *Biotechnology Progress, 20*, 550–560.
6. Barba, D., Beolchin, F., Del Re, G., Di Giacomo, G., & Veglió, F. (2001). Kinetic analysis of *Kluyveromyces lactis* fermentation on whey: batch and fed-batch operations. *Process Biochemistry, 36* (6), 531–536.
7. Siso, M. I. G. (1996). The biotechnological utilization of cheese whey: Review. *Bioresource Technology, 57*, 1–11.
8. Tang, I. C., Yang, S. T., & Okos, M. R. (1988). Acetic acid production from whey lactose by the co-culture of *Streptococcus lactis* and *Clostridium formicoacetium*. *Applied Microbiology and Biotechnology, 28*, 138–143.
9. Kosaric, N., & Asher, Y. (1982). The utilization of cheese whey and its components. *Conservation and Recycling, 5*, 23–32.
10. Patil, G. R., & Gupta, S. K. (1982). High-protein beverage from cheese whey and soy-bean I: Manufacture process. *Indian Journal of Diary Science, 35*(4), 492–496.
11. Sandhu, D. K., & Waraich, M. K. (1983). Conversion of cheese whey to single cell protein. *Biotechnology and Bioengineering, 25*, 797–808.
12. Ben-Hassan, R. M., & Ghaly, A. E. (1994). Continuous propagation of *Kluyveromyces fragilis* in cheese whey for pollution potential reduction. *Applied Biochemistry and Biotechnology, 47*, 89–105.
13. Ghaly, A. E. (1989). Biogas production from dairy manure using continuous mix and nomix mesophilic reactors. *Energy Sources, 11*, 221–235.
14. Ghaly, A. E., Singh, R. K., & Burney, J. R. (1985). Land disposal of cheese whey. CSAE. Paper No. 95-301, Charlottetown, Prince Edward Island, Canada.
15. Ghaly, A. E., Tango, M. S. A., Mahmoud, N. S., & Avery, A. C. (2004). Batch propagation of *Lactobacillus helveticus* with microaeration for production of lactic acid from nutrient supplement whey with high lactose concentration. *World Journal of Microbiology and Biotechnology, 20*(1), 65–75.
16. Yang, S. T., Tang, I. C., & Zhu, H. (1992). A novel fermentation process for calcium magnesium acetate (CMA) production from cheese whey. *Applied Biochemistry and Biotechnology, 34–35*, 569–583.
17. Ghaly, A. E., El-Taweel, A. A., Gomaa, H., Tango, M. S. A., Pyke, J. B., & Cooney, C. (2001). Production of anti-icing/de-icing agents from cheese whey. Proceedings of 11th World Conference of Food Science and Technology, Soul, Korea.
18. Ghaly, A. E., Tango, M. S. A., Pyke, J., & Davidson, M. (2001). Production of biodegradable plastics from cheese whey. Proceedings of 11th World Conference of Food Science and Technology, Soul, Korea.
19. Ghaly, A. E., & El-Taweel, A. A. (1995). Effect of lactose concentration on batch production of ethanol from cheese whey using *Candida pseudotropicalis*. *Transactions of the ASAE, 38*(4), 1113–1120.
20. Meulemans, C. C. E. (1987). The basic principles of UV-disinfection of water. *Ozone Science and Engineering, 9*, 299–314.
21. Qualls, R. G., Flynn, M. P., & Johnson, J. D. (1983). The role of suspended particles in ultraviolet disinfection. *Journal of the Water Pollution Control Federation, 55*(10), 1280–1285.
22. Khomich, V. A., Soloshenko, I. A., Tsiolko, V. V., & Mikhno, I. L. (1998). Investigation of principle factors of the sterilization by plasma DC glow discharge. ICPP & 25th EPS Conference on Controlled Fusion and Plasma Physics, 29 June–3 July, Prague, Czech Republic, ECA, vol. 22C, 2745–2748.
23. VanOsdell, D., & Foarde, K. (2002). Defining the effectiveness of UV lamps installed in circulating air ductwork. Final Report, prepared for the Air-Conditioning and Refrigeration Technology Institute,4100N.Fairfax Drive, Suite 200, Arlington, VA 22203;ARTI-21CR/610-40030-01.
24. Linda, M. (1998). UV pasteurization update. [online] Available: http://www.nysaes.cornell.edu/pubs/press/1998/cider_uv_past.html. [2004, 8 July].
25. Brewster, M. E., Chung, K. Y., & Belfort, G. (1993). Dean vortices with wall flux in a curved channel membrane system: A new approach to membrane module design. *Journal of Membrane Science, 81*, 127–137.
26. Ghogomu, J. N., Guigui, C., Rouch, J. C., Clifton, M. J., & Aptel, P. (2001). Hollow-fibre membrane module design: comparison of different curved geometries with Dean vortices. *Journal of Membrane Science, 181*(1), 71–80.
27. Mallubhotla, H., & Belfort, G. (1997). Flux enhancement during dean vortex microfiltration. *Journal of Membrane Science, 125*, 75.
28. APHA (1967). *Standard methods for the examination of dairy products*. Washignton, DC: American Public Health Association.
29. Darby, J. L., Snider, K. E., & Tchobanoglous, G. (1993). Ultraviolet disinfection for wastewater reclamation and reuse subject to restrictive standards. *Water Environment Research, 65*(2), 169–180.
30. Koch, A. L. (1995). *Bacterial growth and form*. New York: Chapman & Hall.
31. Mitscherlich, E., & Marth, E. H. (1984). *Microbial survival in the environment*. Berlin: Springer Verlag.

32. Rajala, R. L., Pulkkamen, M., Pessi, M., & Heinomen, T. H. (2003). Removal of microbes from municipal wastewater effluent by rapid sand filtration and subsequent UV irradiation. *Water Science Technology, 47*(3), 157–162.
33. Wright, J. R., Sumner, S. S., Hackney, C. R., Pierson, M. D., & Zoecklein, B. W. (2000). Efficacy of ultraviolet light for reducing *Escherichia coli* O157:H7 in unpasteurized cider. *Journal of Food Protection, 63*(5), 563–567.
34. Harrington, W. O., & Hills, C. H. (1968). Reduction of the microbial population of apple cider by ultraviolet irradiation. *Food Technology, 22*, 117–120.
35. Beltran, J. A. G., & Canovas, G. V. B. (2005). Reduction of *Saccharomyces cerevisiae*, *Escherichia coli* and *Listeria innocua* in apple juice by ultraviolet light. *Journal of Food Process Engineering, 28*, 437–452.
36. USEPA (1999). Wastewater technology fact sheet. Ultraviolet disinfection. Office of Water. Environmental Protection Agency, Washington, D.C. EPA 832-F-99-064. [online] Available: http://www.epa.gov/owm/mtb/uv.pdf. [2004, 30 June]
37. Koutchma, T., Stuart, S. K., Stuary, C., & Parisi, B. (2004). Ultraviolet disinfection of juice products in laminar and turbulent flow reactors. *Innovative Food Science and Emerging Technologies, 5*, 179–189.
38. Cengel, Y. A. (2003). *Heat transfer: A practical approach* (2nd ed.). Boston, MA: McGraw-Hill.
39. Ujhidy, A., Nemeth, J., & Szepvolgyi, J. (2003). Fluid flow in tubes with helical elements. *Chemical Engineering and Processing, 42*, 1–7.
40. Yang, R., & Chang, S. F. (1993). A numerical study of fully developed laminar flow and heat transfer in a curved pipe with arbitrary curvature ratio. *International Journal of Heat and Fluid Flow, 14*(2), 138–145.
41. Patankar, S. V., Pratap, V. S., & Spalding, D. B. (1974). *Journal of Fluid Mechanics, 62*(3), 539–551.
42. Nemeth, J., & Bucsky, G. (1997). Secondary flow generated in curved flow. *Hungarian Journal of Industrial Chemistry, 25*, 91.
43. Webster, D. R., & Humphrey, J. A. C. (1997). Traveling wave instability in helical coil flow. *Physics of Fluids, 9*(2), 407–418.
44. Tran, M. T. T., & Farid, M. (2004). Ultraviolet treatment of orange juice. *Innovative Food Science and Emerging Technologies, 5*(4), 495–502.
45. Abu-ghararah, Z. H. (1994). Effect of temperature on the kinetics of wastewater disinfection using ultraviolet radiation. *Journal of Environmental Science and Health, A29*(3), 585–603.
46. USEPA (2002). The environmental technology verification program. Trojan Technologies Incorporated. [online] Available: http://www.epa.gov/etv/pdfs/vrvs/02_vr_trojan.pdf. [2005, 10 Nov].