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The Effects of Mass Flow Rate in an Indirect Ultra-High Temperature Processing System

[1]T.H. Varzakas and [2]A.E. Labropoulos
[1]Department of Processing of Agricultural Products,
School of Agricultural Sciences,
Technological Educational Institute of Kalamata, Hellas, Greece
[2]Department of Food Technology and Nutrition,
Technological Educational Institute of Athens, Egaleo 12210 Athens, Greece

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Abstract: The effect of mass flow rate on product temperature and residence time were studied in a helically coiled, indirectly steam-heated, vertical flow, laboratory Ultra High Temperature (UHT) system equipped with automatic temperature control and recording units. With a mass flow rate of 0.54 to 3.03 kg min^{-1}, the Reynolds number (Re) values ranged from 1,500 to 128,000 in the various sections using water as the test product. Holding times were calculated on the basis of holding tube length and velocity. A computer program was applied to predict the temperatures of the product as a function of residence time for the preheating, heating, precooling and cooling heat exchange sections of the UHT unit.

Key words: Mass flow rate, UHT process system

INTRODUCTION

Increased process temperatures, combined with decreased process times and faster heat transfer, result in fewer undesirable physicochemical effects and a more even time-temperature distribution while maintaining the sterilizing or pasteurizing value (Hallstrom, 1972). Thus, High Temperature-Short Time (HTST) and Ultra-High Temperature (UHT) continuous flow heating systems have been developed to replace vat systems. HT processes involve heating the product by either of two methods (1) direct heating, in which heating of the product involves direct contact with culinary steam and (2) indirect heating, in which heating of the product is accomplished through a barrier wall. Indirect heating systems do not contaminate or dilute the product and do not require vacuum treatment, but could result in fouling or burn-on, resulting in poorer heat transfer efficiencies than with direct heating systems.

Processing of UHT milk is normally carried out commercially in indirect heating plants in which the temperature of milk is raised by passage through a tubular heat exchanger. In such a plant, the quantity of milk that can be processed between two successive cleaning operations is limited by the amount and rate of deposition of fouling material. Under modern processing conditions most fouling generally occurs in the hottest regions of the plant (120-140°C) (Grandison, 1988).

Indirect UHT systems consist most commonly of plate or tube-type heat exchange systems. The helically coiled tube type system can withstand large changes in pressure, which permits the use of

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Corresponding Author: T.H. Varzakas, Department of Processing of Agricultural Products, School of Agricultural Sciences, Technological Educational Institute of Kalamata, Hellas, Greece

the high flow rates necessary to maintain turbulent flow, especially during the processing of highly viscous foods (Reddy, 1971). The critical (Re_{cr}) for fluid foods processed in a helically coiled tube system was first determined by Ito (1959).

The combination of variables that serve as a guide for predicting whether the flow is turbulent oor laminar is known as the Reynolds number. Applications of turbulent flow and calculations of N_{Re} values in fluid flow food processes are discussed by Webb (1964). The point of transition from laminar to turbulent flow is called the critical Re.

Burton (1969) noted that natural or induced turbulence in a flow system would increase the rate of heat transfer owing to an increase in the heat transfer coefficient. Farrall (1963) recommended the establishment of turbulent flow conditions to minimize heat damage of process products. Natural turbulence arising from high velocities is needed to achieve turbulent flow conditions involving high heat transfer rates (Burton, 1972). Burton (1972) also noted that there are considerable differences in the time-temperature cycles to which the product is subjected in different process systems. It is clear that more basic information on fluid flow variables and heat exchange characteristics would contribute to increased processing efficiency, reduced operation problems (e.g., burn on) and overall improved quality of products processed in helically coiled tube, indirect heat exchanger systems.

Sahoo *et al.* (2002) designed and tested a laboratory model indirect type helical tube UHT milk sterilizer. The holding section was designed based on the Arrhenius model to reduce *B. stearothermophilus* microorganisms in the milk by 8 log cycles at a sterilization temperature of 150°C with a residence time of 2.64 sec. The helical double tube cooling section modeling and simulation was carried out to cool milk from 150 to 90°C.

Milk fouling is the main cause of progressive decline in the rate of heat transfer in a UHT milk sterilizer, which results in a drop in milk outlet temperature as the processing advances. Increasing steam temperature is one of the ways to overcome the drop in milk outlet temperature and prolong the operating time before the processing is stopped for cleaning of deposits in the heat exchanger. A computer model was developed by Nema and Datta (2005) for the accurate control of milk temperature as affected by fouling calculating accurately the increase in steam temperature required for maintaining the desired milk sterilization temperature.

A number of attempts have been made earlier to cope with the problem of fouling which include design of fouling resistant equipment i.e., scraped surface heat exchanger, advanced Clean-In-Place (CIP) techniques to remove deposit easily and various controls on processing parameters. A new type, the cartridge exchanger (Margettai, 1985) was designed so that product flows faster and more evenly than in a plate heat exchanger. Alternative processes also resist fouling: in the APV Baker ohmic heating process (Skudder and Biss, 1987) foods are heated by direct application of electric current.

This investigation was undertaken to determine the pertinent flow and heat transfer characteristics for evaluating the effectiveness of a coiled tube heat exchanger indirect UHT system for evaluation of chemical degradation in liquid foods such as milk. Microbiological studies should also be conducted simultaneously.

Calculated residence time-temperature profiles of the heated fluid in the coil tube heat exchangers, for a range of mass flow rates corresponding to turbulent flow, provide a basis for establishing operating conditions in the system. Once the rates of mass flow at the various pump speed settings are established, Reynolds numbers, average velocities and corresponding holding times of a process operation can be calculated.

MATERIALS AND METHODS

UHT system variables were determined on the basis of the flow properties of the food product in the system. Since whole milk does not deviate appreciably from the Newtonian behavior of water

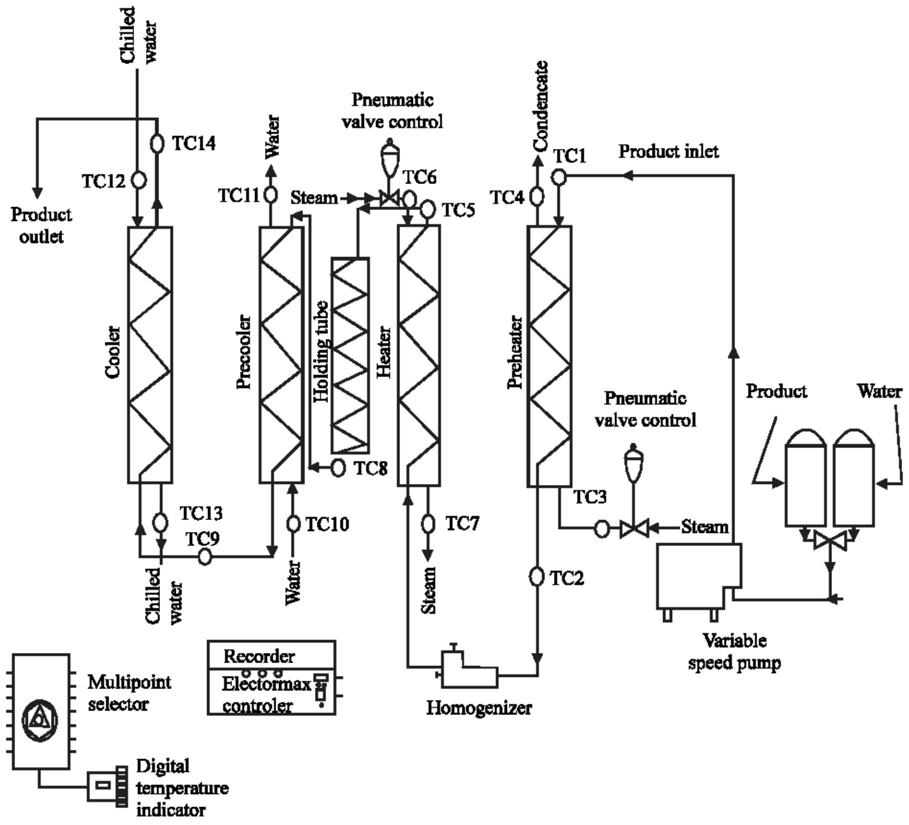

Fig. 1: A Laboratory indirect UHT system (Note: TC1…14 -Thermocouples)

(Webb *et al*., 1974), tap water was used for standardization of mass flow rates in this study. This study was carried out in the Laboratory of Food Engineering, Technological Educational Institute of Athens.

Heat Exchange System

Figure 1 is a helically coiled tube, indirect UHT system used in this study. The system provided accurate temperature control within±1°C and permitted processing of the milk over a wide range of flow variables under closely controlled conditions. The system consists of the following major units: (1) a pump and holding vats, (2) heat exchange and holding sections and (3) temperature controllers and recording instruments.

A high-pressure piston pump (Manton-Gaulin Co., Inc., Everett, MA), with pressures adjustable up to 34.5 Mpa through the setting of motor speeds (General Electric Co.), was used to obtain the desired velocities and holding times in the UHT system.

The four heat exchange sections-preheater, heater, precooler and cooler-were made of type 316 stainless steel tubing with a length of 7.31 m each, 2.65 mm inside diameter (I.D.) and 3.18 mm outside diameter (O.D.) in 0.45×0.33 m stainless steel shells. A schematic drawing of a heat exchange section is shown in Fig. 2. The holding section was also made of type 316 stainless steel tubing with a length of 8.26 m, 4.6 mm I.D. and 6.4 mm OD. The mean diameter (D) of the coils was 60.3 mm.

The temperature of the heated and heating media for each section during UHT operation were measured by in-line copper-constantan termo-couples. The readings were displayed on an automatic

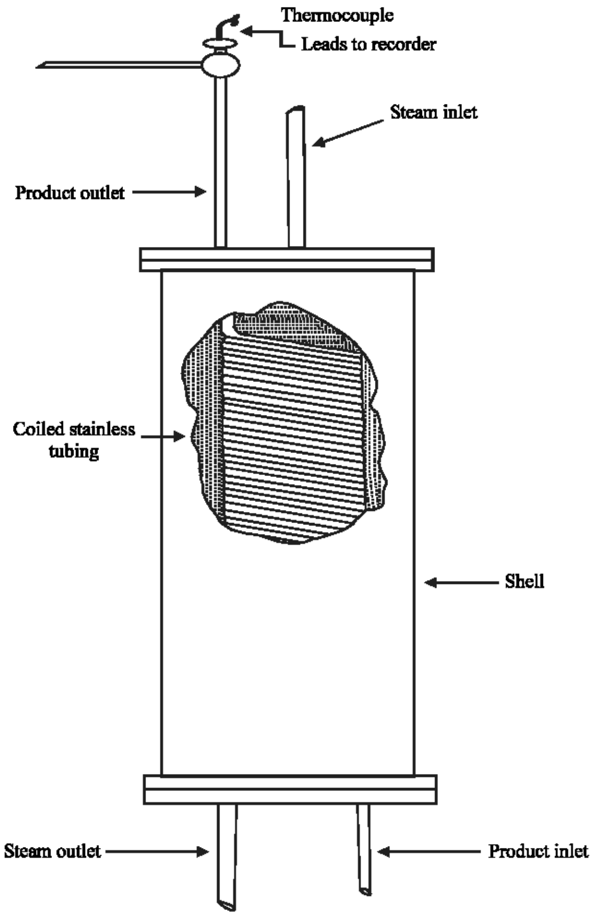

Fig. 2: The heat exchange section shown for heating in the UHT process system. Preheating, precooling and cooling sections are similar

electronic digital recording potentiometer (Omega Engineering Inc., Stamford, CT) joined to a multiple-point dial distributor from the same company. The heat treatment temperature was controlled by a solid-state Electromax signal controller (Leeds and Northrup), which regulated the steam flow to the preheating and heating chambers by air activated valves.

The system included two 18.9 L vats, one to hold the product and the other to hold water for pre-standardizing and cleaning purposes. The vats were joined to a common pipe through valves so that flow could be directed from either vat into the system. A homogenizer was used between the preheating and heating sections for certain purposes (i.e., milk homogenization). The heating medium was 641.2 kPa saturated steam. Tap and chilled water were used, respectively, in precooling and cooling heat exchangers.

A triple concentric tube heat exchanger is an improved version of the double pipe heat exchanger. Improvemenst include a large area per unit length available for heat transfer and better overall heat transfer coefficients due to higher fluid velocities in the annular regions (Zuritz, 1990). Milk flows in the annular region whereas steam flows in the outer and central tube.

Table 1: Experimental temperatures of heating and heated media in the sections of an indirect UHT system for a 149°C process and 5 kg min^{-1} mass flow rate

No. of thermocouples	Location of thermocouples	Medium	Temperature (°C)
Preheater			
1	Inlet	Product[1]	60
2	Outlet = Heater inlet	Product	79
3	Inlet	Steam	98
4	Outlet	Condensate and steam	68
Heater			
5	Outlet = Holder inlet	Product	149
6	Inlet	Steam	154
7	Outlet	Steam and condensate	154
Holder			
8	Outlet = Precool inlet	Product	149
Precooler			
9	Outlet = Cooler inlet	Product	47
10	Inlet	Tap water	31
11	Outlet	Tap water	46
Cooler			
12	Inlet	Chilled water	2
13	Outlet	Chilled water	7
14	Outlet	Product	10

[1] Water was used as testing product to establish operation condition for milk processing

Flow Property Variables

Flow conditions are defined by certain flow variables, including the geometrical shape of the flow channel, the flow rate and/or flow velocity and the physical properties of the liquid, all of which are incorporated into a single dimensionless group, the Reynolds number (Re). It is well known that the flow rate through any cross section is constant for steady flow in any continuous stream of fluid. Thus, the average velocity can be determined by measuring the mass flow (kg min^{-1}) according to the continuity flow equation:

$$Q = \rho_1 A_1 \bar{V}_1 = \rho_2 A_2 \bar{V}_2 \tag{1}$$

Where,

Q = Mass flow rate (kg sec^{-1})

$\bar{V}_i$ = The average fluid velocity (ft sec^{-1})

ρ_i = The fluid density (kg m^{-3}), at location I

A_i = Pipe cross sectional area (m^2) at location i

$$Q = \frac{w}{t_s} \tag{2}$$

Where,

w = Mass of collected sample (kg)

t_s = Time to collect sample (sec)

The Re_{cr} can be calculated for a helically coiled tube using Eq. 3 given by Ito (1959):

$$Re_{cr} = 2\times10^4\ (d/D)^{0.32} \tag{3}$$

Where,

d = The internal tube diameter (m)

D = Mean coil diameter (m)

According to Ito, this equation gives good agreement with experimental results in the range $15 < D/d < 8.6\times10^2$.

Temperature Distribution

Table 1 shows the temperature as a function of distance ($T\rho_x$) and/or time in the various sections of the UHT system was computed on the basis of Eq. 4, as used by Reddy (1971) for similar vertical heat exchangers. Aldrich (1972) proved experimentally that Eq. 4 correctly defines the temperature at any point in the coiled tube if the inlet and outlet temperatures of the heating and heated media are known:

$$T\rho_x = \frac{T_{s_1}T_{\rho_1} - T_{s_2}T_{\rho_1} - \left(T_{\rho_2} - T_{\rho_1}\right)\left(T_{s_1} - T_{\rho_1}\right)\left(\frac{T_{s_2} - T_{\rho_2}}{\left(T_{s_1} - T_{\rho_1}\right)}\right)^{x/L'}}{\left[T_{s_1} - T_{\rho_1} - \left(T_{s_2} - T_{\rho_2}\right)\right]} \qquad (4)$$

Where,

Tp_x = Temperature (°C) of product at distance × from a heat exchanger inlet
x = Distance from the inlet of a heat exchanger of length L, ρ and s refer to product and heating medium and 1 and 2 represent inlet and outlet, respectively.

From the analysis of the heat transfer to the milk, the outlet temperature can be calculated. Due to gradual increase in fouling thickness, the outlet temperature will drop and the milk will remain under-sterilized and therefore the shelf life and safety of the milk cannot be assured. To maintain a constant outlet temperature or to check the drop in outlet temperature of the milk, wall temperature has to be increased proportionately, which can be obtained by suitably increasing the temperature or pressure of the steam (Nema and Datta, 2005).

Both the dimensionless distance-temperature and the residence time-temperature distributions for the UHT system were calculated and are shown in Fig. 3 and 4.

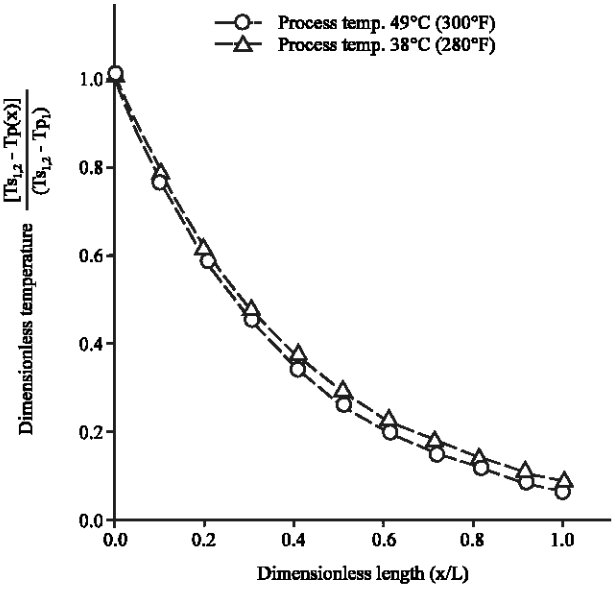

Fig. 3: Typical axial temperature distribution of water heated in a helically coiled tube heat exchanger

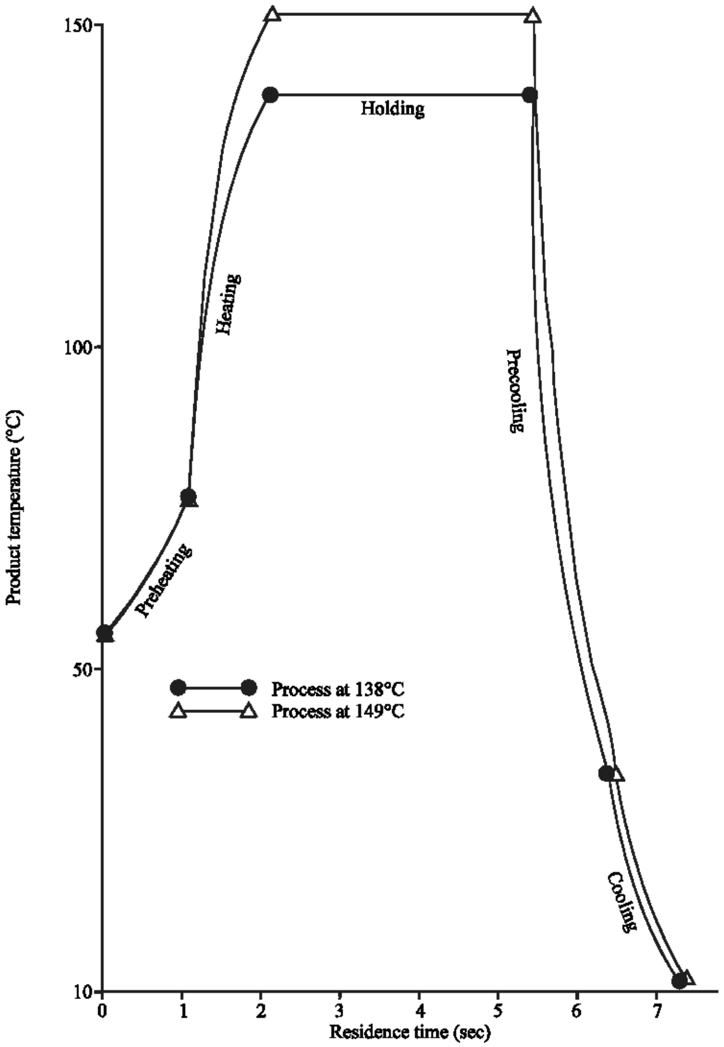

Fig. 4: Residence time and temperature distribution curves at the various heat exchange and holding sections of the indirect UHT system for 138 and 149°C processes, at a flow rate of 2.3 kg min^{-1}

The product holding time is directly proportional to holding tube length. The calculated length of time depends upon the average product velocity in the holding tube. Therefore, by assuming residence time and heat exposure uniformity among individual particles of the product, the average holding time for the process can be determined using the equation

$$t_h = L / \bar{V} \tag{5}$$

in which t_h = the holding time (sec), L = the holding tube length (m) and $\bar{V}$ = the average holding tube velocity (m sec^{-1}).

RESULTS AND DISCUSSION

Process Variables

To achieve the objectives of this study it was necessary to evaluate the UHT system over various flow rates permitted by the pump used in the system. Since the flow conditions reflect Re value, it was useful to calculate Re over the flow rates of 0.54 to 3.03 kg min^{-1}. The values ranged from 128,000 in the heating section (149°C, 2.03 kg min^{-1}) to 1,500 in the cooling section (10°C, 0.54 kg min^{-1}). Overall, the calculated Re values varied from 3,400 to 22,900 in the various sections at a mass flow rate of 0.54 kg min^{-1} and from 19,000 to 128,000 at a mass flow rate of 3.03 kg min^{-1}. On the other hand, the Re values were 50,000, 95,500, 55,000, 30,400 and 14,200, respectively for the preheating exchanger, heating exchanger, holding tube, precooling exchanger and cooling exchanger at a mass flow rate of 2.27 kg min^{-1} for an average velocity of 7.39 m sec^{-1}.

It can be seen that the average velocities for the heat exchange and holding sections vary, respectively, from 1.7 to 9.7 m sec^{-1} and from 0.6 and 3.4 m sec^{-1} in the mass flow rate range of 0.5 to 3.0 kg min^{-1} (Table 2). Increasing velocity increased Re and reduced the holding time. Since holding time is a function of the average product velocity and holding tube length, it appeared more reasonable to change the velocity rather than the length of the tube for the holding time calculations.

Figure 5 shows plots of mass flow rate versus the Re values for the various sections of the UHT system at certain temperatures of the various sections of UHT system. These curves make it possible to predict the flow conditions in the various sections of the system for a specific mass flow rate.

On the other hand, to attain turbulent flow conditions, the Re values were also compared to the critical Re = 7.350 and kept at higher values for each section of the UHT system. The ratio of the mean diameter of the coils to the inside diameter of the tube (60.3/2.6 = 22.8) of the heat exchange sections lies in the range 15< D/d < 860 of good agreement for the critical Re equation with experimental results as reported by Ito (1959) and Sahoo *et al*. (2002).

Figure 6 shows the three dimensional relationship between product temperature, mass flow rate and Reynolds number. Use of this figure allows selection of flow rate and temperature to evaluate the Reynolds number which is used as an indication of the flow conditions (turbulent or laminar).

Temperature Distribution

The temperature, as a function of residence time and mass flow rate for the helically coiled, indirect heated UHT system was determined at 0.1 sec residence time intervals, using a computerized procedure and Eq. 4. It is important to note that Eq. 4 has been experimentally proven for similar heat exchangers by Aldrich (1972). The residence times in the various heat exchange and holding sections of the UHT system at different flow rates are presented in Table 3. For example, at a mass flow rate of 2.3 kg min^{-1}, the preheating and heating time to raise the product temperature from 60 to 149°C was

Table 2: Average velocities in the heat exchangers and holding section of the helically coiled tube, indirect UHT processing system

	Average velocity (m sec^{-1})	
Mass flow rate (kg min^{-1})	Heat exchange section	Holding section
0.5	1.7	0.6
0.9	2.9	1.0
1.4	4.4	1.5
1.8	5.8	2.0
2.3	7.2	2.5
2.7	8.7	3.0
3.0	9.7	3.4

Table 3: Process residence times at various mass flow rates and holding sections in the helically coiled tube indirect UHT system

	Average residence time (sec)		
Mass flow rate (kg min^{-1})	Heat exchange sections	Holding section	Total residence time (sec)
0.5	4.3	13.7	30.9
0.9	2.6	9.2	19.6
1.4	1.7	5.5	12.3
1.8	1.3	4.1	9.3
2.3	1.0	3.3	7.3
2.7	0.8	2.7	5.9
3.0	0.7	2.5	5.3

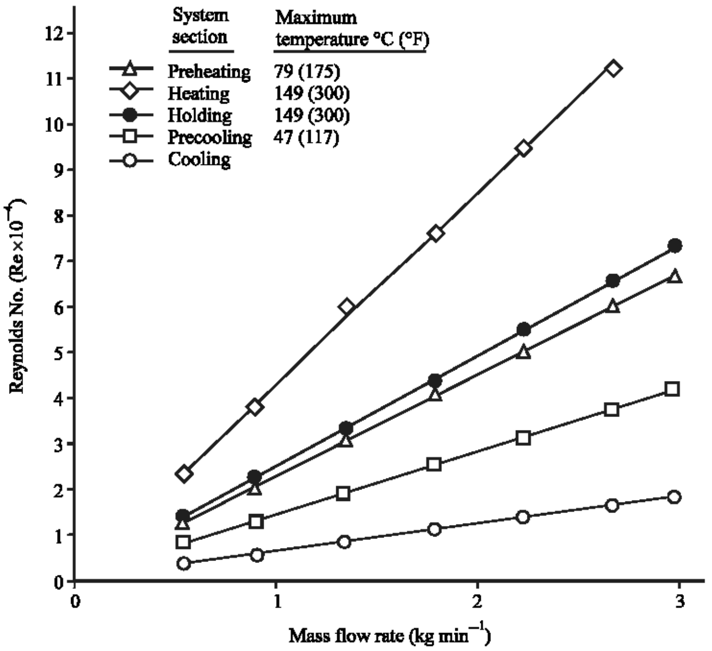

Fig. 5: Reynolds number-mass flow rate linear profiles as related to maximum product temperature obtained in the various heat exchange and holding sections of the UHT system

2.0 sec, the holding time at 149°C was 3.3 sec and the precooling and cooling time to decrease the product temperature from 149 to 10°C was 2.0 sec. The total residence time at the above mass flow rate was 7.3 sec.

Profiles of temperature distribution (Fig. 4), for the 2.3 kg min^{-1} flow rates are exponential with reference to residence time in the heat exchanger sections. Similar exponential time-temperature relationships in a straight tube, steam heated system were reported by Charm (1978). Analytical data for determining the axial temperature distribution of the heated fluid were obtained for two processes at 138 and 149°C. Typical plots of the axial temperature distribution (heating section) of the heated fluid, shown in Fig. 4, were logarithmic and predictable from Eq. 4, provided the initial and final temperatures of the heated and heating media were known.

A linear distance-temperature relationship in a straight tube turbulent flow system was observed by Read *et al*. (1956). Since uniform heating by electrical resistance was used, a linear relationship was expected. Thus, the type of heating may influence the rate of heating. Hallström (1972) reported that the rate of heating is a function of the flow channel shape, the flow velocity and the physical

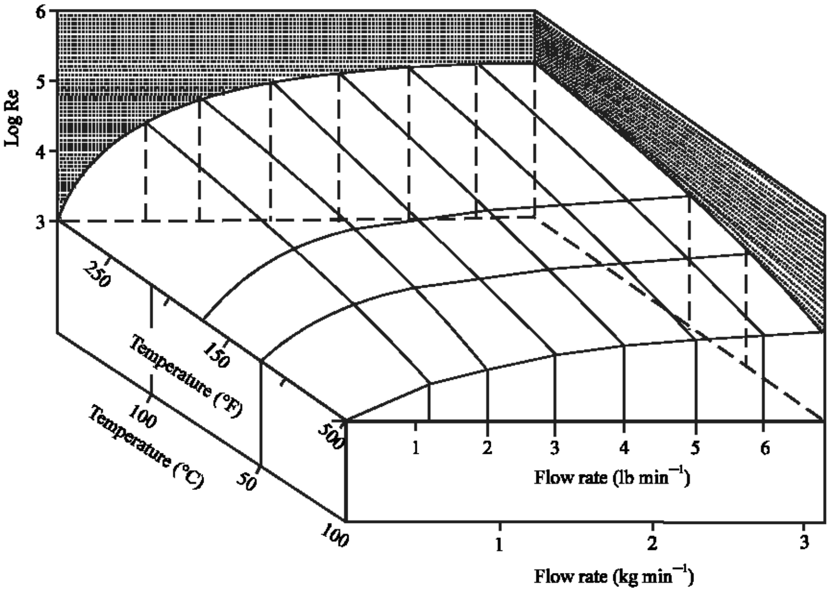

Fig. 6: Relationships between product temperature, mass flow rate and Reynolds number in the coiled tube, indirect UHT system using water as a test material

properties of the fluid. It is well known that the critical factor related to the heat transfer is the overall heat transfer coefficient. This factor is dependent on the heat transfer characteristics of the wall, physical properties of fluid, the nature of the heating medium and the temperature difference between the heating and heated media.

The time-temperature relationships shown in Fig. 7 indicate that the rates of heating and cooling u values, for a constant process temperature increase progressively as the mass flow rate of the product increases. The total time to heat at a mass flow rate of 0.9 kg min^{-1} was approximately three times greater than at a rate of 2.7 kg min^{-1}. Thus, the temperature change per 0.1 sec in the UHT system increased in direct proportion to the flow rate if other parameters are constant. Even with large variations in mass flow rate of the heated media, the residence time-temperature distributions were essentially exponential (Fig. 6) and can be further analyzed using available mathematical techniques. Lower flow rates, which increase residence times, necessitate heat treatments, thus creating problems such as burn on during the processing of milk.

Further studies of flow and heat transfer characteristics and additional experimental verifications should be carried out, since the lack of such information is the factor limiting further application of coiled-tube heat exchange systems in the food industries.

The computerized approach and techniques applied in this study can be useful to further work with other fluid foods such as fruit juices as well as non-food products such as pharmaceuticals. Furthermore, the procedures used in this study could be applied to other similar continuous flow process systems.

The results are quite encouraging and suggest further scope for technological improvement in the heat treatment of milk in helical triple tube heat exchangers. This work suggests that the proposed model may be useful for predicting calculated residence time-temperature profiles of the heated fluid in the coil tube heat exchangers, for a range of mass flow rates corresponding to turbulent flow, providing a basis for establishing operating conditions in the system. Once operating conditions are established they can be implemented for commercial UHT milk sterilizers with suitable modifications.

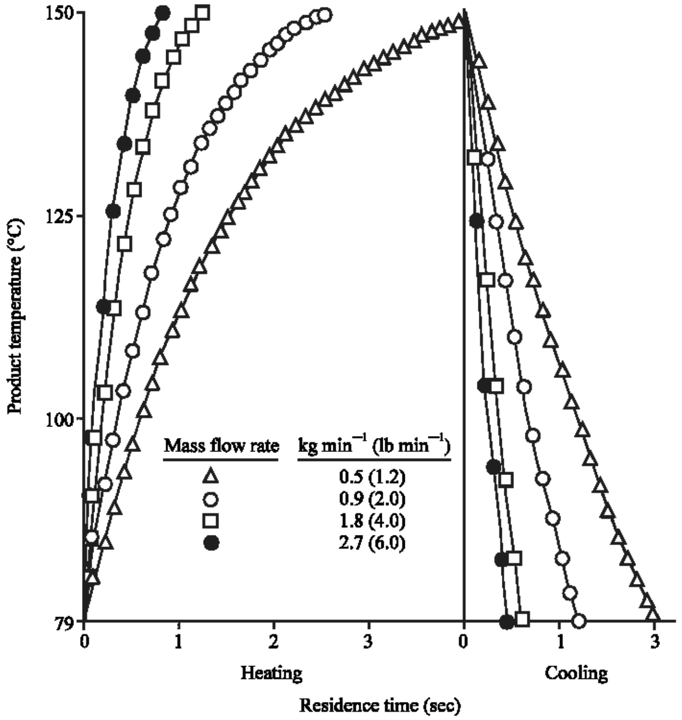

Fig. 7: Residence time-temperature profiles of heating and cooling curves in UHT system at 149°C and at different flow rates

CONCLUSIONS

Calculated residence time-temperature profiles of the heated fluid in the coil tube heat exchangers, for a range of mass flow rates corresponding to turbulent flow, provide a basis for establishing operating conditions in the system. Once the rates of mass flow at the various pump speed settings are established, Reynolds numbers, average velocities and corresponding holding times of a process operation can be calculated.

Typical plots of the axial temperature distributions of the heated fluid lead to the conclusion that such distributions are exponential even with large variations in rates of mass flow.

The results of the experiments and the calculations obtained can be useful to further work with different fluid food and non-food products.

Further studies of flow and heat transfer characteristics and additional experimental verifications are recommended, since the lack of such information is the factor limiting further application of coiled-tube heat exchange systems in the food industries.

In conclusion, the computerized approach and techniques applied in this study can be useful to further study with various fluid foods such as fruit juices and other non-food products such as pharmaceuticals. Furthermore, the procedures used in this study could be applied to other similar continuous flow process systems.

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