Food Engineering Progress
Vol. 10, No. 1. pp. 6~13 (2006.2)

Potential Milk Fouling Area in Plate Heat Exchangers

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Abstract

Milk fouling is prone to occur at the eddy flow area on plate surface when temperature differential between two streams exceeds 10-14°C in plate heat exchangers (PHEs). A verified 2D hydro- and thermodynamic model was applied to correlate the potential milk fouling area with the system parameters such as the plate aspect ratio, defined as a ratio of the plate height to its width, and the inlet flow rate. Development of eddy flow areas and hot zones can be visualized by simulation based on the 10-channel PHE system with countercurrent flow pattern. A simple equation developed to predict empirically the eddy flow area ratio showed that the area of eddy flow is proportional to the inlet flow rate and reciprocal of the plate aspect ratio, with high correlation to the actual measurement (R^2 = 0.989). Most important, the development of potential hot zones as well as eddy flow areas need to be considered during optimization of processing parameters to minimize milk fouling.

Key words: 2D model, flow distribution, plate aspect ratio, flow rate, eddy flow, hot zone, CIP

Introduction

Fouling is a common dairy industry-wide issue during thermal treatment using plate heat exchangers (PHEs). It induces hydraulic and thermal disturbances and creates the need for cleaning operations every 5-10 hours. Fouling directly contributes toward increased energy costs in operation and maintenance, production losses, and energy and water losses due to the repetitive cleaning operation (Sandu and Singh, 1991). Therefore, a number of studies have been reported in literature to model the fouling problem to improve energy and water use efficiency during PHE pasteurization.

Milk fouling models in PHEs based on 1D representation of the process hydrodynamics have shown limited predictive capability. All 1D formulations are based on unidirectional flow distribution, which is a considerable simplification of the effect of plate geometry used in industry (for example, Das and Murugesan, 2000; Georgiadis and Macchietto, 2000; and Rao, Kumar and Das, 2002). In previous studies such as those by Jun *et al.* (2004), the 2D model that accounts for the hydrodynamics of fluid flow was capable of predicting the temperature distribu-tion of flow with higher accuracy than 1D model. When the plate aspect ratio is defined as a ratio of the plate height to its width, 1D model produced large prediction errors for PHE with a smaller plate aspect ratio; while 2D model prediction followed the magnitudes and trends of the experimental data more accurately, irrespective of the plate aspect ratio. The 2D model could also identify zones most prone to milk deposits, i.e. eddy flow streams, where the temperature differential between the cold and hot streams, known as a critical fouling factor (Hiddink, *et al.*, 1986), are likely to exceed the threshold values.

The processing parameters such as flow temperature (T) for denaturation of b-LG, temperature differential (DT) between two fluid streams, flow rate, and plate regime have been widely recognized as factors contributing toward fouling during heating of milk (Visser and Jeurnink, 1997). There is a paucity of literature on correlation of the potential milk fouling area with processing parameters. Such a contribution will be timely and beneficial to the dairy industry.

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The intent of this study was to extend and validate the model developed by Jun *et al.* (2004) to different plate aspect ratios and inlet flow rates. The simulated flow and temperature distributions of fluid milk are used to determine the zones most prone to milk fouling.

Methodology

To compute the flow distribution in PHE channels the full Navier-Stokes (N-S) equations were solved with respect to the coordinate system shown in Fig. 1. The plate surface is assumed to be flat and smooth. The governing 2D Navier-Stokes flow equations include the continuity and momentum equations in the Cartesian coordinates, as given by (Kays, 1966):

Continuity: $$\frac{\partial u}{\partial x}+\frac{\partial y}{\partial y}=0 \quad (1)$$

x-momentum:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

y-monentum:

$$\frac{\partial v}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+v\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \quad (3)$$

where u is the kinematic viscosity, r is the density, P is the pressure, t is the time, u and v are the velocity components in x and y directions, respectively.

The transient energy equation for a 2D constant property, incompressible flow is given by:

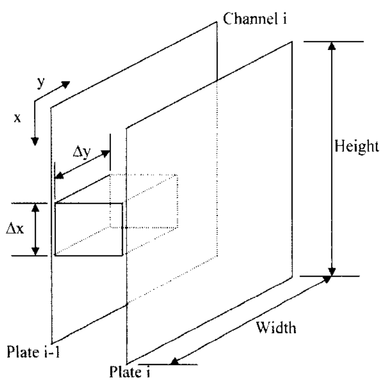

Fig. 1. Control volume of fluid inside the channel in 2D.

Energy:

$$e_i\rho_i Cp_i\left(\frac{\partial T_i}{\partial t}+u_i\frac{\partial T_i}{\partial x}+v_i\frac{\partial T_i}{\partial y}\right)=U_i(T_{p(i-1)}+T_{pi}-2T_i) \quad (4)$$

$$\delta_p\rho_p Cp_p\frac{\partial T_{pt}}{\partial t}=U_i(T_i+T_{i+1}-2T_{pi}) \quad (5)$$

where T_i is the temperature of fluid in channel i, T_{pi} is the temperature of plate i, Cp_i and Cp_p are the respective specific heats of fluid in channel i and plate, ρ_i and ρ_p are the respective densities of fluid in channel i and plate, e_i is the distance between the plates, δ_p is the plate thickness, and U_i is the overall heat transfer coefficient in channel i.

The 2D N-S equations need to be transformed into a simpler form in order to eliminate the pressure term between the momentum equations; otherwise solving the flow equations is considerably more involved. The vorticity-stream function approach is known to be applicable for 2D cases (Özisik, 1994).

For 2D Cartesian coordinate system considered, the vorticity vector, w is given by:

$$\omega=\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y} \quad (6)$$

and the streamline function, y is defined by:

$$\frac{\partial \Psi}{\partial y}=u,\frac{\partial \Psi}{\partial x}=-v \quad (7)$$

with the definition of streamline function, the continuity equation (1) is identically satisfied. The transformation of the dependent variables from "u, v" to "ω, ψ" is applied to equations (2) and (3) to obtain the equation for the vorticity, w, upon elimination of the pressure term, which leads to:

$$\frac{\partial \omega}{\partial t}+u\frac{\partial \omega}{\partial y}+v\frac{\partial \omega}{\partial y}=v\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right) \quad (8)$$

An additional useful relationship for streamline function derived using equations (4) and (5) is:

$$\frac{\partial^2 \Psi}{\partial x^2}=u,\frac{\partial^2 \Psi}{\partial y^2}=-\omega \quad (9)$$

Thus, using the vorticity-streamline approach, it transforms the mixed elliptic parabolic 2D N-S equations in the "u, v" variables to the vorticity-transport equation which is parabolic in time and an elliptic streamline equation in the "ω, ψ" variables.

For finite-difference approximation of these equations, the upwind differencing discretizes the convective terms and the central differencing to discretize the second derivatives with respect to the space variables. The time step Δt satisfying the stability constraint for 2D model is given by (Özisik, 1994):

$$\Delta t \le \left\{ \frac{|u|}{\Delta x} + \frac{|v|}{\Delta y} + 2\nu\left(\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} \right) \right\}^{-1} \tag{10}$$

where $|u|$ and $|v|$ are the absolute values of x and y velocity components at each grid point, and the time step, Dt, to satisfy equation (8) can be determined when combination of $|u|$ and $|v|$ produces a maximum value.

The time-dependent mathematical simulation was done in MATLAB v.6.0 (MathWorks, Inc., Natick, MA, USA) environment. The 2D domains with different plate aspect ratios were discretized with Δx = 0.01 m and Δy = 0.01 m, which were sufficiently small to approximate the space derivatives with reasonable accuracy while ensuring convergence. The contour plots of streamline and temperature of fluid in PHE were drawn using Tecplot v.8.0 (Amtec Engineering, Inc., Bellevue, WA, USA).

Results and Discussion

The hydrodynamic and thermodynamic performance of fluid milk in PHEs were simulated with respect to different plate aspect ratios ranging between 1.5 and 6 while keeping the height constant as 60 cm, and different inlet flow rates (0.003 to 0.2 m/s). The ranges of the applied system parameters were determined based on the values used for model validation by Jun *et al.* (2004), i.e. the plate aspect ratio of 3 and inlet flow rate of 0.03 m/s. From industrial standpoints, the inlet flow rate lower than 0.003 m/s is unacceptable since it cannot fill the total heat transfer area and channel gaps, thus leading to lowered heat transfer coefficient. On the other extreme, the inlet flow rate higher than 0.2 m/s is likely to exceed the maximum design pressure of the specific PHE model besides the deficient energy transfer, resulting in additional capital investment related to equipment such as hydraulic pump and number of plates for energy balancing. The simulation was accomplished using the operating conditions and flow configuration presented in Table 1 and Fig. 2. For model simplification, PHE consists of 10 channels with all countercurrent flow patterns with assumption that the inlet flow rates of both the hot and cold streams are equal, and the hot stream is unidirectional. Given Δx = 0.01 m and Δy = 0.02 m, discretizing of Δt = 0.1 s (< minimum 0.33 s) for PHEs with different plate aspect ratios and inlet flow rates satisfied the stability criterion for the explicit solution, as given by equation (10). Calculated Reynolds numbers (N_{Re}) were ranging between 500 and 700, determined at the reference velocity for each system, which was laminar flow.

Table 1. Operating conditions used for 2D simulation

Conditions	Values	
	Cold water	Hot water*
Inlet temperature (°C)	14	70
Inlet flow rate (m/s)	0.003, 0.02, 0.1, and 0.2	0.003, 0.02, 0.1, and 0.2
Flow pattern	All countercurrent	
Total number of plates	10	
Targeted plate for comparison	5th (cold water)	
Discretization	Δx = 0.01, Δy = 0.02	
	Δt = 0.1	

*Flow direction of hot water is considered in 1D for even comparison.

PHEs with different flow rates

Figure 3 shows the streamline plots of fluid milk that

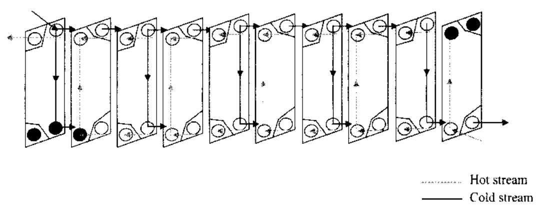

Fig. 2. Flow configurations for PHE.

flows down through the plate surface from the top right to the bottom right, drawn based on four different inlet flow rates (0.003, 0.02, 0.1, and 0.2 m/s) with a plate aspect ratio of 3. Model predictions clearly show that there is a likelihood of eddy flow streams on the top left, implying the zone most prone to milk fouling (Jun et al., 2004). It is observed that as the inlet flow rate increases, the area of eddy flow also increases. The higher inlet velocity the stream has, the more straightforward it flows down along the right of plate surface and thus, causing the eddy flows at the left.

Based on the flow distribution in Fig. 3, the temperature profiles of cold stream in 5th plate of PHE with different flow rates were calculated, as shown in Fig. 4(a). The temperature contour of the cold stream with a low inlet velocity of 0.003 m/s is nearly horizontal below the middle of plate, indicating that the flow stream is fully and evenly distributed. However, as the inlet flow rates increase, the temperature contours become more curvilinear along with marked stream direction. The top left of plate is found to have temperature contours substantially different from other areas, showing the regional high temperature values. The model prediction for flow temperature can identify clearly the existence of eddy flow trapped due to the extreme angular momentum of the stream. Yet another hot zone developed at the bottom left, which is attributed to a lack of the amount of flow so that even the same energy from inlet hot stream in the next channel can lead to an excessive temperature rise in the zone.

Since milk fouling is significantly affected by flow temperature (T) and temperature differential (ΔT) between hot water and cold milk, the temperature differential patterns needs to be calculated where the flow temperature exceeds 65^{o}C, above which β-LG starts to aggregate (Visser & Jeurnink, 1997). In Fig. 4(b), the contour levels of temperature differential more than 10^{o}C are displayed based on suggestion of Hiddink, Lalande, Maas and Streuper (1986), which stated that temperature differential to cause fouling should exceed 10-14^{o}C. It can be seen in the figure that as inlet flow rate increases up to 0.02 m/s, the potential fouling area grows up from the bottom to the middle of plate along with the plate boundaries. As the inlet flow rates increase further, the potential fouling areas developed at the bottom left diminish to become negligible whereas the fouling area at the top left appears and then becomes smaller. The contour line of temperature differential at the top left is expected to be most prone to milk fouling due to the synergistic effect of the eddy flow causing the deposition of milk components such as whey protein and minerals. It is noted that the milk fouling area

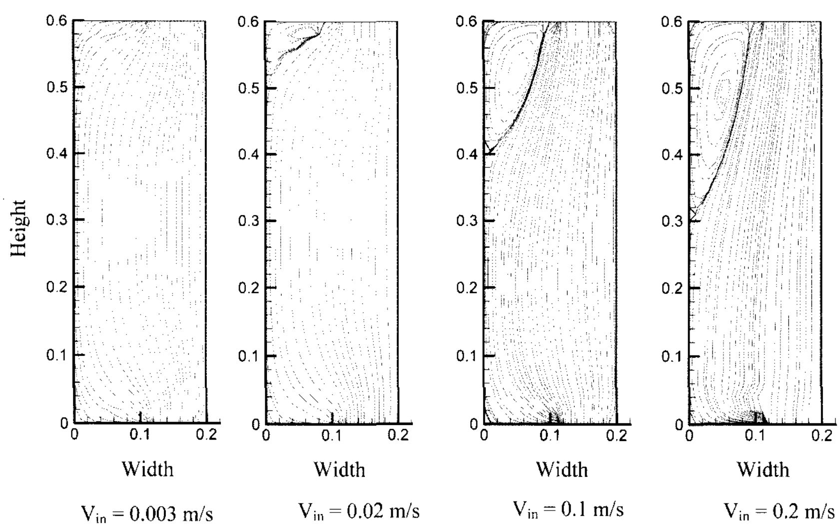

Fig. 3. Simulated streamline plots of fluid milk in PHE of a plate aspect ratio of 3 with different inlet flow rates (0.003, 0.02, 0.1, and 0.2 m/s).

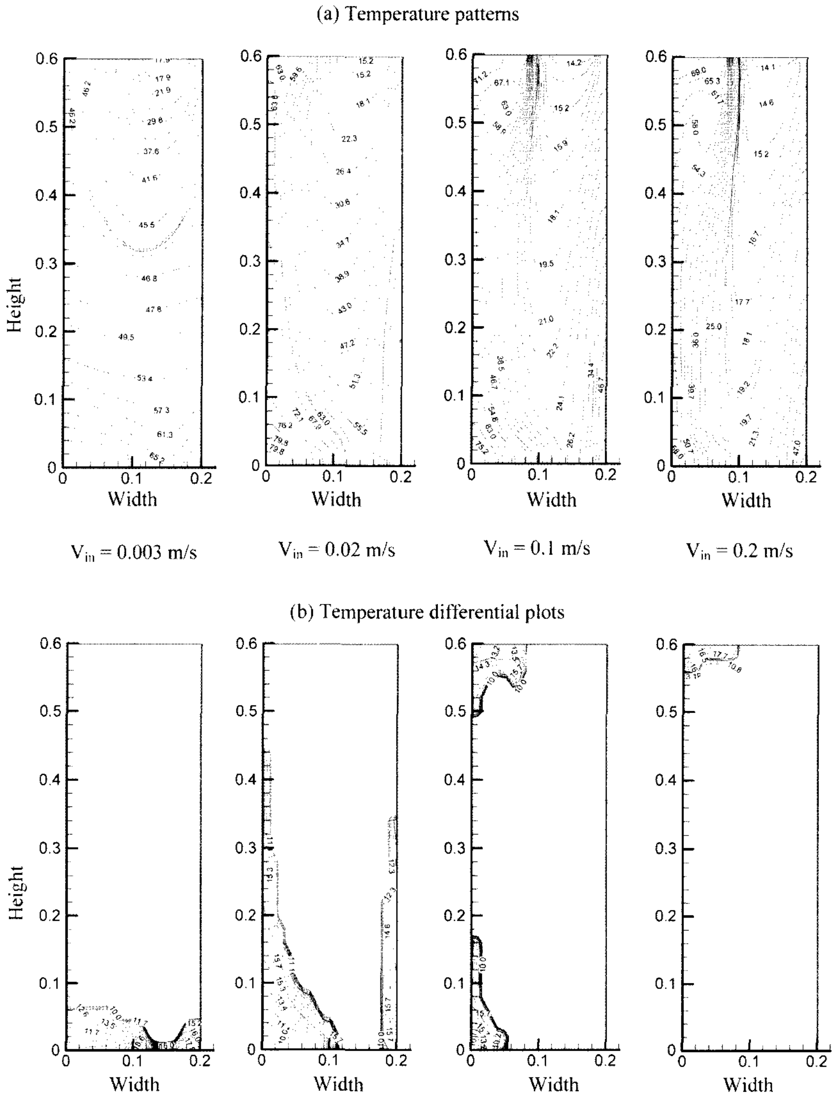

Fig. 4. Simulated temperature patterns (a) and temperature differential plots (b) of fluid milk in PHE of a plate aspect ratio of 3 with different inlet flow rates (0.003, 0.02, 0.1, and 0.2 m/s).

prediction based on temperature differential patterns tends to diminish, as expected, by an increase of the inlet flow rate.

PHEs with different plate aspect ratios

Figure 5 shows the streamline plots of fluid milk in PHE of different plate aspect ratios with a constant inlet flow rate of 0.03 m/s. Clearly, the area of eddy flow stream increases as the plate aspect ratio decreases. Such an observation suggests that an increase of plate width with the same inlet flow rate leads to insufficient pressure drops in parallel direction for driving the flow stream from right to left.

Similar to Fig. 4, Figure 6 shows the temperature patterns of cold milk (a) and temperature differential between hot water and cold milk (b) simulated based on the hydrodynamic performance of fluid milk in Fig 5. For all different plate aspect ratios, similar temperature patterns are obtained. The hottest zone in Fig. 6(a) is located at the bottom left, showing the temperature contour values up to 80°C. It is noted that there is a weak correlation of the temperature contour lines with the

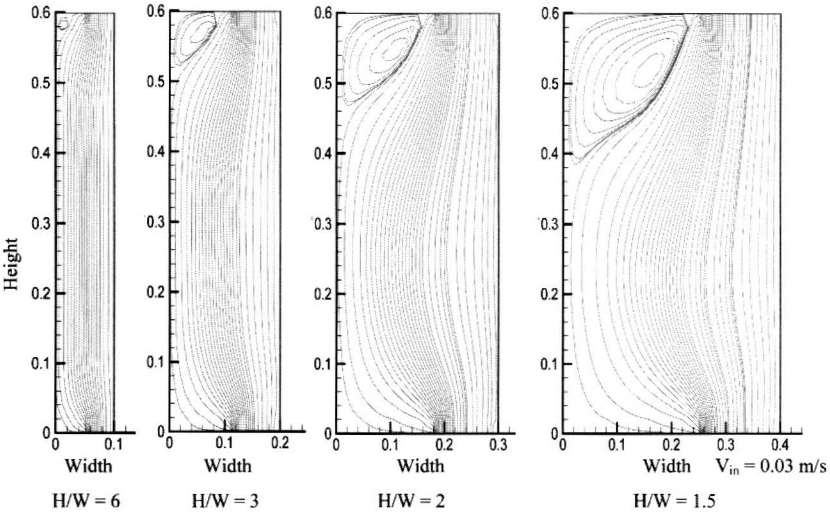

Fig. 5. Simulated streamline plots of fluid milk in PHE of different plate aspect ratios (6, 3, 2, and 1.5) with a constant inlet flow rate (0.03 m/s).

existence and size of eddy flow at the top left, compared to Fig. 4(a). As the plate aspect ratio decreases and the plate surface becomes wider in Fig. 6(b), the potential fouling area, where the temperature differential exceeds 10°C, develops to predominantly cover the left area of plate surface. The simulation results are markedly similar to the previous work by Delplace, Leuliet and Tissier (1994), displaying the deposit of whey protein on heat exchanger surface after six hours of operation.

Assessment of potential milk fouling areas

Since the eddy flows shown in Figs. 3 and 5 are most prone to milk fouling, the irregularly shaped areas were measured using a planimeter of accuracy ±0.2% (Nr. 316E, Gebrüder HAFF, Hazlet, NJ) and summarized in Table 2.

Based on information given in Table 2, a simple equation to correlate the eddy flow area ratio (eddy flow area/total plate area) with the plate aspect ratio and inlet flow rate was developed using SigmaPlot v.6.0 (SPSS Inc., Chicago, IL, USA) given by:

$$A_{eddy} = 100\times\left(\frac{0.0567}{x_1}\left(1.657+144x_2-\frac{0.0027}{x_2}\right)-0.0097\right) \quad (11)$$

where A_{eddy} is the eddy flow area ratio (%);

x_1 is the plate aspect ratio;

x_2 is the inlet flow rate (m/s).

The data obtained from equation (11) is in good agreement with the actual measurement as shown in Table 2, with a high correlation coefficient of 0.989. The model sensitivity was also verified by comparing the predicted eddy flow area ratio (21.7%) with the data (23.3%) obtained in the plate with a different shape and velocity combination, i.e. $x_1 = 2$ and $x_2 = 0.1$ m/s.

The developed equation can pave the way toward a practical approach to optimize the process for minimizing milk fouling. The smaller the inlet flow rate

Table 2. Quantitative estimation of eddy flow areas in Figs. 3 and 5.

	Plate aspect ratio	Inlet flow rate (m/s)	Eddy flow area/total plate area (%)
Fig. 2	3	0.003	0
	3	0.02	2.5
	3	0.1	10.3
	3	0.2	15.4
Fig. 3	6	0.03	0.4
	3	0.03	2.8
	2	0.03	7.4
	1.5	0.03	12.5

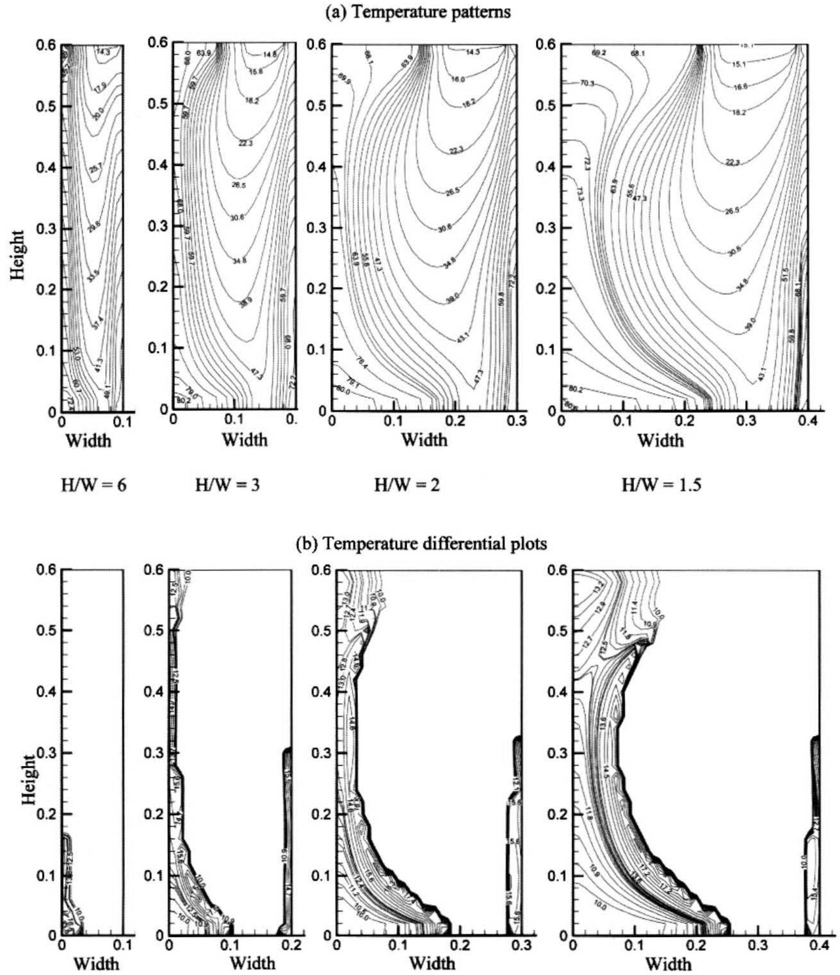

Fig. 6. Simulated temperature patterns (a) and temperature differential plots (b) of fluid milk in PHE of different plate aspect ratios (6, 3, 2, and 1.5) with a constant inlet flow rate (0.03 m/s).

and the larger the plate aspect ratio, the smaller the eddy flow area is to be expected. However, at the same time, an increase of the hottest zone at the corner opposite to the outlet, where there is a lack of flow amount, should be noted. The above two parameters influencing the occurrence of potential milk deposits on the plate surface are closely interrelated with the outputs demanded by the industry such as the production yield and energy efficiency. Most important, optimizing the cleaning-in-place (CIP) process is also a function of the processing parameters such as temperature and flow rate. The milk deposits accumulated on the surface due to eddy flows during the thermal dairy process could be removed by the CIP process only with different flow patterns, i.e. multi-stage cleaning with a variety of flow rates. The knowledge of the hydro- and thermodynamic performance of fluid milk in PHE in consideration of the key processing parameters is valuable not only for minimizing milk fouling during thermal processing but also for cleaning practices.

Conclusion

A 2D hydro- and thermodynamic model was applied to evaluate the correlation between the potential milk fouling area and the plate shape, i.e. the plate aspect ratio in relation to the inlet flow rate. It was observed that increases in the size of eddy flow, most prone to milk deposits, are caused by an increase in the inlet flow rate and a decrease in the plate aspect ratio. The hot zones that satisfied the temperature criteria, i.e. T > 65°C and DT >10°C were assumed to be the potential weak spots susceptible to fouling. An eddy flow area belonging to hot zone is expected to have a synergistic impact on development of milk fouling. A simple equation developed to predict the eddy flow area as a function of the inlet flow rate and plate aspect ratio was consistent with the actual measurement with R^2 value of 0.989. The model prediction will be useful for determining the optimal operating conditions of PHEs to minimize the fouling area through a further realistic assessment by the industry.

Acknowledgement

The authors acknowledge the USDA, milk safety program, PAES 3880 and the PA Agricultural Experimental Station for support of this effort.

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