Numerical Modelling of Fouling in PHE using Milk- A Review

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Abstract— Fouling of Plate heat exchangers is a major problem in Diary industry. When the milk is heated above 65°C there is chemical transition of proteins in milk. This transition is called as Milk denaturation. The milk initially has Native protein, due to increase in temperature of milk there is transformation of protein from Native to Denaturated and from Denaturated to Aggregated, but only aggregated protein sticks to the surface of PHE. Due to this aggregation a layer is formed on surface which reduces the heat transfer & thus the performance of PHE. This phenomenon is called as Fouling of Plate Heat Exchanger.

Key words: Fouling, Mathematical modelling, Dynamic simulation, Heat transfer

I. Introduction

Heat exchangers are used extensively and regularly in process industries such as refineries, power plants, cold storages, and food industries. Among the wide variety of heat exchangers, plate heat exchangers are widely used in diary and food processing plants, chemical industries, power plant, and cooling systems due to the ease of maintenance, cleaning, their compact designs, and their excellent heat transfer coefficient characteristics.

Fouling of plate heat exchangers (PHE) during milk processing is a major problem with a negative impact on operating costs and product quality. It also leads to a rise in pressure drop across the exchanger and possible deterioration in product quality due to failure of the process fluid to reach the required temperature. Another serious problem associated with fouling is the cleaning of fouled surfaces by means of costly and time-consuming techniques where environmentally offensive chemicals are employed. Given the economic impact of fouling in milk heat exchangers, it is not surprising that there is a considerable amount of literature available on modelling of the fouling process. There seems to be an agreement that thermal denaturation of whey protein betalactoglobulin plays a major role in the fouling process, certainly when the temperature is about 90°C.

II. Description of Fouling Model

- Proteins react in both the bulk as well as the thermal boundary layer in the milk. Native protein N is transformed into denaturated protein D, in a first order chemical reaction. The denaturated protein then reacts to give aggregated protein A in a second order chemical reaction.
- Mass transfer between the bulk as well as the thermal boundary layer takes place for each protein.
- Only the aggregated protein is deposited on the wall. The deposition rate is directly proportional to the concentration of aggregated protein in the thermal boundary layer.
- The fouling resistance to heat transfer is directly proportional to the thickness of the deposit.

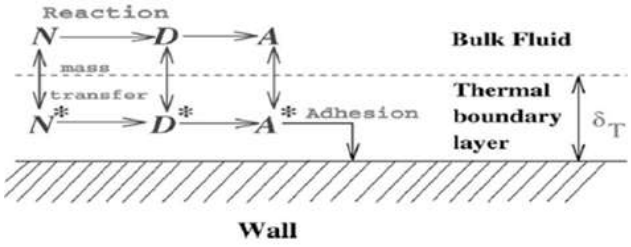

Fig. 1: The protein reaction scheme in fouling model [2]

III. General Assumptions for Modelling

- No diffusion of heat was considered in the axial direction.
- The flowrate and temperature profiles were taken uniform across the channel and plate width.
- Each fluid was assumed to split equally between all related channels.
- Heat losses to the environment were negligible.
- The head and follower parts of the PHE were assumed to be insulated and serve as adiabatic plates.
- The variation of the physical properties of milk with temperature were neglected.
- No diffusion was considered with respect to the channels width and, instead, mass transfer was modelled via mass transfer coefficients.

IV. Governing Equations for Fouling in Plate Heat Exchanger

Following are the three major governing equations which are involved.

A. *The Following Is Energy Equation for Channel*

$$e_j\rho_j Cp_j\left(\frac{\partial T_j}{\partial t}+n_j u_x\frac{\partial T_j}{\partial x}\right)=U_j(T_{p(j-1)}+T_{pj}-2T_j)$$

The following is energy equation for plates

$$\delta_p\rho_p Cp_p\left(\frac{\partial T_{pj}}{\partial t}\right)=U_j(T_j+T_{j+1}-2T_{pj})$$

B. *Species Transport Equation*

Material balances of proteins in the bulk are given by the following set of equations

Native protein:

$$\frac{\partial C_{Nj}}{\partial t}+n_j u\frac{\partial C_{Nj}}{\partial x}=-k_{No}\exp\left[-\frac{E_N}{(RT_j)}\right]C_{Nj}+\frac{\partial}{\partial x}\left[D_N\left(\frac{\partial C_{Nj}}{\partial x}\right)\right]-\frac{k_{mN}}{\delta_T}(C_{Nj}-C^*_{Np})$$

Denaturated protein

$$\frac{\partial C_{Dj}}{\partial t}+n_j u_x\frac{\partial C_{Dj}}{\partial x}=k_{No}\exp\left[-\frac{E_N}{(RT_j)}\right]C_{Nj}-k_{Do}\exp\left[-\frac{E_D}{(RT_j)}\right]C^2_{Dj}+\frac{\partial}{\partial x}\left[D_D\left(\frac{\partial C_{Dj}}{\partial x}\right)\right]-\frac{k_{mD}}{\delta_T}(C_{Dj}-C^*_{Dp})$$

Aggregated protein

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$$\frac{\partial C_{Aj}}{\partial t} + n_j u_x \frac{\partial C_{Aj}}{\partial x} = k_{Do} \exp\left[-\frac{E_D}{(RT_j)}\right] C_{Dj}^2 + \frac{\partial}{\partial x}\left[D_A\left(\frac{\partial C_{Aj}}{\partial x}\right)\right] - \frac{k_{mA}}{\delta_T}(C_{Aj} - C_{Ap}^*)$$

C. Mass Deposition Equation

$$Mass_p(x) = \frac{\lambda_d Bi_p(x) \rho_d}{U_o}$$

V. REVIEW OF PAPERS

Georgiadis et. al [2] proposed a mathematical model and simulation of plate heat exchanger under milk fouling with the help of detailed dynamic models. It is known that when milk is heated above 65°C β-lactoglobulin becomes unstable. The main benefit of the above model was that it could be used to simulate the transient behaviour of several types of PHEs including counter-current and co-current arrangements. Here the Discretization of species concentration equation was done with the help of second-order backward finite difference method with 20 elements. To know aspects of fouling behaviour three different configurations with complex flow arrangements were taken into consideration they conducted experiment for each plate and the results indicate that fouling was low in the first channel and increases as plate number increases, this was due to less temperature at these channels. Fouling was low at low inlet concentration and higher Reynolds number. Arrangement 3 had less Fouling as milk temperature was low.

Youcef et. al (2007)[3] then developed a fouling model based on the hydrodynamic and thermodynamic performances of the PHE to predict fouling. Here chemical reaction model was used in a 2D dynamic model to predict milk deposit patterns on the plate surfaces with more accuracy. A counter-current flow PHE with 12-channel was used for analysis. Discretization of equations was done with help of Explicit finite difference method with 40 elements. The results concluded that deposit was primarily controlled by the protein aggregation reaction. Once the milk was heated, the protein aggregates and attaches on the wall. The overall heat-transfer coefficient gradually decreases along length of the channel. The concentration of protein decreases due to the denaturation process made by the increase in the milk temperature during the heating. A 30% reduction with respect to initial concentration of β-lactoglobulin was observed. The deposition of mass decreases with an increase in the Reynolds number because of higher removal rate of foulant due to increase in shear forces. They concluded that a decrease in pasteurization temperature may save energy without affecting the product quality.

Jafari et. al (2011)[4] then prepared a threshold model. In threshold model a graph was created with help of algebric equations, in this graph a threshold curve was formed, the points above the graph show specific results and points below show other results. In this context this threshold model has a curve in which the points above the curve represent fouling zone and the points below represent non fouling zone. In this model they have considered that the rate of accumulation is the subtraction of rate of deposition and rate of removal. The proposed model has two parts. The first part deals with fouling formation and the second part deals with a removal of fouling. A static flow lets the deposit attach the surface, and high velocity decreases the fouling formation due to high value of shear stress on heat transfer surface. Also increasing the fluid flow velocity causes increase in value of overall heat transfer coefficient and consequently decrease in amount of deposit. On the other hand, high velocity requires powerful pump that may lead to surface erosion. As bulk temperature increases there is decrease in concentration of the exit protein, which means the amount of aggregated protein has been increased.

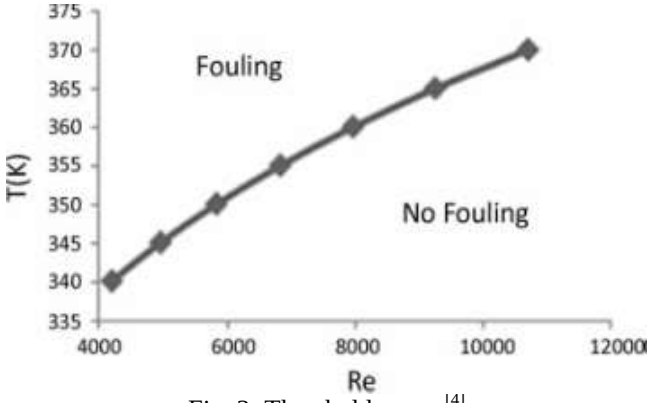

Fig. 2: Threshold curve [4]

Fryer (1993) et. al [5] aimed to inspect the fouling process and find the regions of the system in which the controlling processes occur. Though the processes that give rise to fouling are complicated, it may be possible to know one of process that controls the fouling rate over a series of temperature and flow conditions. Experiments were conducted to examine whether fouling from whey protein concentrates is controlled by a bulk or a Surface reaction or it is controlled by mass transfer or reaction controlled in a tubular heat exchanger. Experimental results display that the temperatures of the laminar sub layer at the inlet and the bulk fluid at the outlet are similar, this recommends that bulk processes were partly responsible for the fouling processes. But they concluded that these results were not conclusive. It was not proposed that bulk processes were the only ones involved, or that they will be important in all situations.

Jun (2006) et. al [8] emphasised on fouling prediction in 2D based on hydrodynamic and thermodynamic performances of PHE. The aim here was to use the chemical reaction model to 2D dynamic model to know the milk deposit patterns on the plate surfaces. For validation purpose they used two PHE configurations PHE 1 with 12 channel and PHE 2 with 20 channels. They concluded that aggregation rate of unfolded protein was observed to rise exponentially with increase in wall temperature, due to a reduction in flow rate as well as heat transfer coefficient. Also when milk is distributed evenly to each channel, so milk will be heated less by heating medium resulting in less fouling. The occurrence of fouling was generally more along the right side of plate surface covering about 92% to 52% of the total amount of deposits and especially on the bottom right, providing a mass deposit rate of 41 g/m2 during operation of 20 h. Moreover, inadequate amount of milk flow accelerates the particles in suspension to settle down onto the heat transfer surfaces while losing a self-cleaning function.

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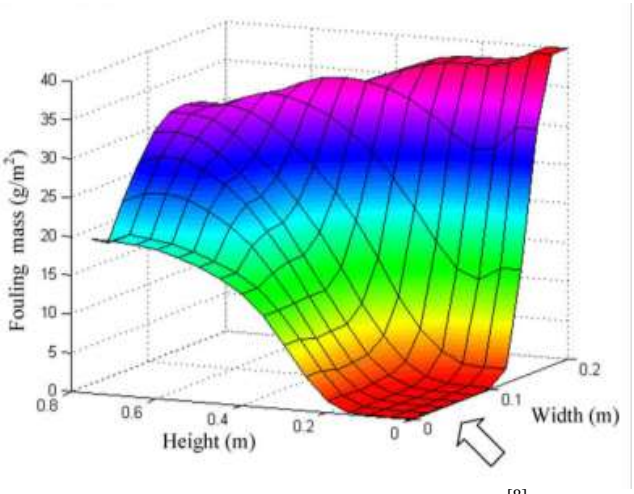

Fig. 3: Simulated fouling distribution [8]

Thonon et. al (2010)[9] has conducted experiments on plate heat exchanger using different corrugation angle (30° 45° 60°) using different particle with different velocity. The results show that increase in the corrugation angle leads to lower values for the fouling resistance. For low corrugation angles, the flow is almost in line of the corrugation, while in case of higher corrugation angles the flow is more complicated and that induces high turbulence. As the turbulence is increases the wall shear stress increases which do not permit particle to adhere. Similarly there is a strong velocity effect on the fouling behavior for all geometry. For the 30° angle, the fouling is 10 times lower when the velocity is increased to three times. The fouling resistance is directly proportional to the particle concentration and is inversely proportional to the particle diameter and also increasing the particle diameter will lead to a reduction of the minimal shear stress required to remove the particles.

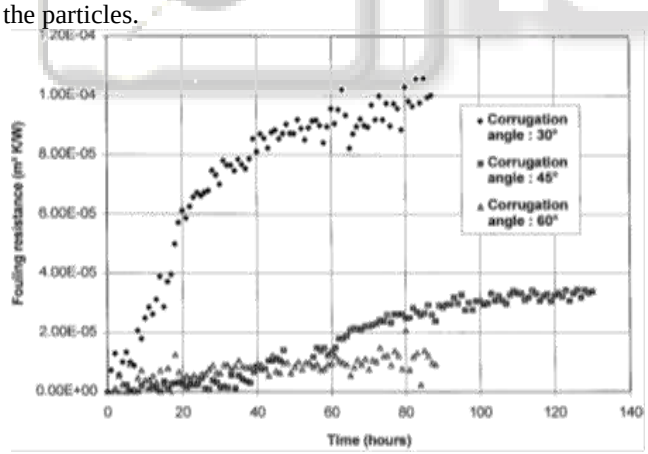

Fig. 4: Fouling resistance for three corrugation angles at a velocity of 0.5 m/s [9]

Blochl et. al (1990)[10] investigated the effect of particle size on particulate fouling during convective sensible heat transfer to liquids. Two types of experiments were conducted. In first experiment, the effect of particle size on particulate fouling was investigated. In second experiment the fouling behaviour of different fluid combinations was investigated. The asymptotic fouling resistance and the initial fouling rates both increased with increase in particle concentration. For each particle size, a linear growth of asymptotic fouling with increase in concentration was observed for lower particle concentrations. With rise in particle concentration, a peak fouling resistance was reached for each particle size. More rise of concentration had no influence on asymptotic fouling. At lesser concentrations the particles were kept in suspension by the shear forces resulting from pumping of the fluid and from its motion through valves and orifices. At high particle concentrations these forces were not sufficient to avoid aggregation. With increase in particle size the asymptotic fouling resistance decreases continuously. The predicted asymptotic fouling resistance has a minimum value at approximately 5µm. For larger particles, fouling should increase because of increase in inertia forces.

VI. CONCLUSION

Various authors have studied the process of fouling on heat exchangers and these studies could be divided in two groups, the first group is related to studies related to development of fouling prediction mathematical model, these models may be 1D or 2D. While the other group is related to studies related to evaluating the effect of changing input parameters on fouling. From the study it can be concluded that Fouling is proportional to temperature of milk and inversely proportional to Reynolds number or velocity of milk.

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