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Conjugate fluid flow and kinetics modeling for heat exchanger fouling simulation

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ABSTRACT

Thermal treatment of fluid foods represents a major unit operation in the food industry, to ensure the product's safety and quality features. But during the thermal treatments of such sensible fluids in common plate heat exchangers, food constituents such as proteins can be thermally damaged and precipitated to form fouling that greatly affect the treatment efficiency and alter the product's desired features.

Computational Fluid Dynamics simulations can then be successfully exploited, bringing forth temperature and velocity information that yield for deposit distributions when coupled to biochemical notations for thermal denaturation of fluid constituents.

The present work exploits such modeling for a single-channel heat exchanger during pasteurization of milk. The model enforces a conjugate system of differential equations to a heat exchanger's corrugated plate to combine flow, heat transfer and local transport of β-lactoglobulin. A preliminary computation has been performed that could be applied to geometry optimization (different corrugation shape and orientation) and for a variety of biochemically evolutive products.

1. Introduction

The increasing attention on safety and quality of medium and long time shelf-life has stimulated the application of various and optimized thermal treatments, in order to get flavor and nutritional values closer to those of untreated foods. For this very reason, thermal treatment of fluid foods is one of the most important unit operation in the dairy (milk) or fruit juices industry, to ensure microbial safety and extend storage. Energy delivery is a paramount parameter (through temperature) in controlling the alterations among the fluid constituents during its biochemical evolution, and must be coupled with time exposure, to quantify the energy intake. Therefore the temperature–time coupling is the most important feature to be optimized in this technology, but recently the attention has been drawn upon the management of the treatment device as well, as reviewed by Jun and Puri [6].

The device generally entitled to realize an indirect heating of fluid food is the Plate Heat Exchanger (PHE) (Fig. 1), which features a number of favorable aspects: flexibility to allow different fluid treatment, safety, high thermofluid efficiency, high turbulence to enhance heat transfer and low weight/surface ratio [11]. Nevertheless, during its working cycles, a PHE is subject to a complex phenomenon which causes undesired material accumulation (or fouling) along its working surfaces. Fouling formation and control is a common problem in process industries, causing an increase of capital costs, energy and maintenance time, and a loss of production, together with a meaningful environmental impact: fouling causes increased pressure drop, reduction of working efficiency through the reduction of the heat transfer, and increased downtime due to the frequent cleaning stage, with environmentally offensive chemicals, to ensure stable processing [1,2].

The biochemical fouling mechanism has been long studied specially for milk processing, and its reflected flow-dependent features have favored some complex analyses. As shown by de Jong et al. [12], Georgiadis et al. [3], Georgiadis and Macchietto [4] and Grijspeerdt et al. [5], the denaturation of the β-lactoglobulin (βLG) protein is responsible for fouling for thermal treatment close to 90 °C, while several additional parameters influencing such as milk composition, pH, plate geometry and entrained air.

The optimization of technological process and their operating conditions are nowadays looked upon with the aid of numerical modeling of transfer phenomena. Integration of governing Partial Differential Equations (PDEs) allows for a fundamental and quantitative way to understand complex phenomena which is complementary to the traditional approaches of theory and experiment. This approach is becoming increasingly widespread in basic research and advanced technological applications, cross cutting many scientific fields including biotechnology and food engineering. Again for the dairy industry, Georgiadis and Macchietto [4]

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Nomenclature

α	thermal diffusivity (m^2/s)
c	molar concentration (mol/m^3)
D	mass diffusivity (m^2/s)
K	reaction rate (1/s)
ν	kinematic viscosity (m^2/s)
p	pressure (Pa)
R	source term of reactions ($kg/m^3\,s$)
Re	Reynolds number, based on channel height
ρ	density (kg/m^3)
t	time (s)
T	temperature (K)
$\mathbf{v}$	velocity vector (m/s)

Subscripts

A	aggregated protein
D	denaturated unfolded protein
F	deposited protein
i,j	species
N	native protein
r	reaction
s	superficial
v	volumetric

proposed a mathematical model by integrating a PDEs plug-flow model with the heat convection along the flow direction and the effects of dispersion. Fouling is considered as mono-dimensional at steady state, and different heat exchanger configurations are compared by using a specific software to quantify the fouling distribution in the whole device. The deposit varies linearly with time, specially at the beginning of treatment, and is non-uniform in the different channels considered being more localized in the first flow passages, where temperature is higher. Nema and Datta [9] proposed a model to predict the fouling thickness and the milk outlet temperature in a helical triple tube heat exchanger. The fouling is controlled by temperature and shear stress on the surface of the heat exchanger. The milk outlet temperature was simulated, and the fouling thickness was determined based on the enthalpy balance and assuming a constant heat flux across the heat exchanger wall, but based on empirical considerations leading to a dimensionless fouling factor in the form of a Biot number. Then Jun and Puri [7] have employed a full two-dimensional Navier–Stokes formulation for the flow field, but again the use of a Biot number to calculate the overall heat transfer coefficient prevented a complete conjugate approach. Though still idealized (plates have no corrugations) they showed that the temperature distribution and related fouling could be predicted based on a complex combination of transport equations. A validation was also carried out, which compared favorably with tests, for several thermal and fluid flow conditions, confirming that the deposit is strongly dependent on operating conditions.

It should be insisted here that the complex combination of transport phenomena and technological aspects at hand suggests that the fouling must be retained in a conjugate framework: this means that the transfers of mass and heat are solved simultaneously in both solid (channel wall or fouling surface) and fluid phases, and are strongly coupled through deposition and properties variation due to velocity field and temperature. Therefore an innovative approach is to solve a model in which the mass and energy interface fluxes vary seamlessly in space and time as the solution of field variables, such as velocity. The transport equations contain the macroscopic term of convective transport and a source term allowing for the fouling creation, but the boundary conditions at the internal surfaces are independent on transfer coefficients or on the definition of boundary layers.

Computational Fluid Dynamics (CFD) can be enforced to solve governing PDEs. The detailed flow field study, coupled to the other transport notations, offers a potential of improved performance, better reliability, more confident scale-up, improved product consistency, and higher plant productivity. All these aspects give deeper understanding of what is happening in a particular process or system: it makes it possible to evaluate geometric changes, for example, with much less time and cost than would be involved in laboratory testing, it can answer many "what if" questions in a short time and, finally, it is particularly useful in simulating conditions where it is not possible to take detailed measurements.

In the present work the PDE problem, with the related biochemical notations, has been solved by using a commercial Finite Element solver [13] in order to determine the temperature distribution, the velocity profile and the distribution of the protein deposit. The model is the basis for more specialized computations aimed to minimize fouling, i.e. by modifying the fluid dynamics regime or corrugation shape and orientation. The application of the model could be beneficial to the food and biotechnology industry, suggesting the application of specific heat exchanger geometries for a specific product or process.

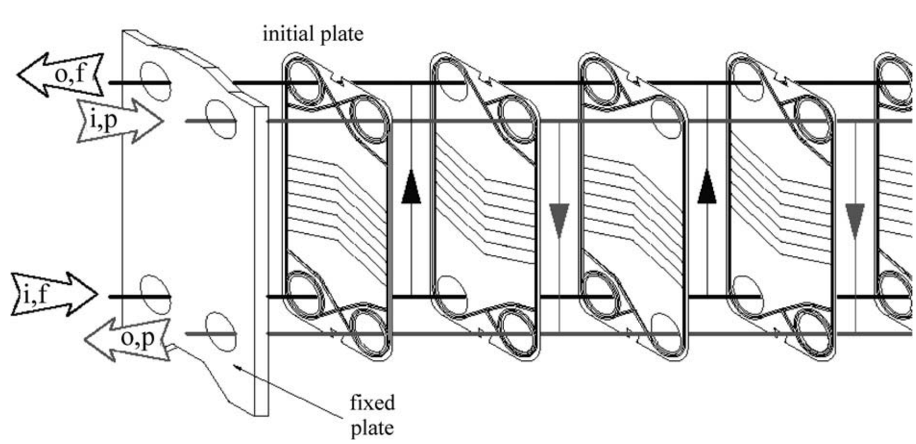

Fig. 1. The stacked PHE arrangement, with indication of streams. The product line with gray lines and arrows (p), and the auxiliary fluid (thermal carrier) with black lines and arrows (f) are reported, respectively, at inlet (i) and outlet (o).