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Effect of calcium content and flow regime on whey protein fouling and cleaning in a plate heat exchanger

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ABSTRACT

Fouling and cleaning with a whey protein concentrate solution in a plate heat exchanger were investigated with a varying calcium concentration (from 70 to 87.5 mg L^{-1}) and under a wide range of hydrodynamic conditions for a bulk fouling fluid temperature, ranging from 60 and 96 °C.

This work demonstrates that increasing the calcium concentration in whey protein concentrate contributes to the amount of fouling and affects the thermal conductivity of the deposit. It was also observed that the fluid flow regime during fouling, impacts the deposit growth, modifies the structure of fouled layers and has a significant consequence on cleaning behaviour.

Finally, a dimensional analysis together with experimental measurements, allowed a relationship to be established enabling prediction of the amount of dry mass deposited locally as a function of the known calcium content, Reynolds number and bulk fluid temperature.

1. Introduction

In the food industry, thermal treatments are often carried out to reduce the microbial load of food products and to deactivate enzymes that would otherwise cause quality loss. The fouling of heated surfaces, inherent to heat treatments, remains one of the major issues in food industry, as this compromises product quality and process efficiency (Visser and Jeurnink, 1997; Jun and Puri, 2007; Mahdi et al., 2009).

Fouling with WPC solutions has been widely investigated over the last twenty years both in PHEs, (Lalande et al., 1984; Daufin et al., 1987; Delplace et al., 1994; Jeurnink and de Kruif, 1995; Christian et al., 2002; Srichantra et al., 2006), or in tubular heat exchangers (THEs) (Delsing and Hiddink, 1983; Gotham et al., 1989; Jeurnink et al., 1989; Belmar-Beiny et al., 1993). Fouling deposits consist of a layer of protein aggregates and minerals, which are mostly calcium phosphate (Tissier and Lalande, 1986). The protein/mineral ratio in the deposits depends on temperature (Burton, 1968).

Protein fouling is mainly due to the protein aggregation resulting from disulphide interchange reactions (−SH/SS) (Lalande et al., 1985; Shimada and Cheftel, 1989; Hoffmann and Van Mil, 1997). Beta-lactoglobulin (BLG) is recognized as the main protein responsible for fouling in milk and milk derivatives (Lalande et al., 1985; Lalande and Rene, 1988).

Lin et al. (2006) reported the effects of ionic calcium on reactions related to casein micelle stability, such as heat stability and susceptibility to sediment formation and fouling. In the case of WPC fouling, the literature also evokes calcium-dependent fouling, yet few quantitative data are available concerning the influence of calcium on the behaviour of whey protein fouling during long experiments in a PHE. It has been recognized that calcium ions substantially affect the interactions between protein molecules (Schmidt et al., 1978) and have a strong impact on the BLG denaturation/aggregation (Jeyarajah and Allen, 1994; O'Kennedy and Mounsey, 2009; Petit et al., 2011). However, the specific interaction between Ca^{2+} and BLG at molecular level are still poorly

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Nomenclature

A	constant defined by Eq. (7) (–)
C_{ca}	calcium concentration (kg m^{-3})
C_{pp}, C_{ph}	specific heat for the product and hot water (J kg^{-1} K^{-1})
d_h	hydraulic diameter (m)
di	internal diameter (m)
e	gap between two consecutive plates (m)
F_T	logarithmic mean temperature difference correction factor (–)
k_d, k_r	coefficients in Eq. (7) (–)
$\dot{m}_p$, $\dot{m}_h$	mass flow rates for the product and hot water (kg s^{-1})
M_d	amount of deposit (kg)
Q	flow rate (m^3 s^{-1})
R	molar ratio within the fouling solution, equal to the calcium concentration divided by the β-lactoglobulin concentration (–)
Re	Reynolds number (–)
R_f	fouling resistance (m^2 °C W^{-1})
S	heat transfer area (m^2)
t	time (s)
$\bar{u}$	average flow velocity (m s^{-1})
U_g	overall heat transfer coefficient (W m^{-2} K^{-1})
v	average crossflow velocity of the fouling solution in the fouling step between two plates of the PHE (m s^{-1})
w	width of the V7 plate (m)
ΔP_0	pressure drop for clean exchanger (mbars)
ΔP	instantaneous pressure drop (mbars)
$\Delta\theta$LMTD	logarithmic mean temperature difference (K)
μ	Newtonian viscosity (Pa s)
ρ	density (kg m^{-3})
θ	temperature (K)

Subscript

h	hot water
i	inlet
o	outlet
j	channel number
p	product

Abbreviations

BLG	beta-lactoglobulin
PHE	plate heat exchanger
WPC	whey protein concentrate

understood (Simons et al., 2002). The presence of calcium ions enhances the heat-induced aggregation of BLG (Sherwin and Foegeding, 1997), and the structure of aggregates was found to depend on a critical molar ratio of calcium to protein (Phan-Xuan et al., 2013).

It has been suggested that three parameters, or combinations of them, might be responsible for calcium-induced protein aggregation (Simons et al., 2002). The first phenomenon is related to intermolecular cross-linking of adjacent negatively-charged or carboxylic groups by the formation of protein–Ca^{2+}–protein complexes (Bryant and McClements, 1998; Hongsprabhas et al., 1999). The second is the intramolecular electrostatic shielding of negative charges on the protein, thereby favouring BLG aggregation by hydrophobic bonds (Hongsprabhas and Barbut, 1997; Roefs and Peppelman, 2001). The third is an ion-induced conformational change, which leads to altered hydrophobic interactions and aggregation at elevated temperatures (Kinsella and Whitehead, 1989; Wang and Damodaran, 1991). The latter indicates that calcium acts principally on BLG aggregation (Mulvihill and Donovan, 1987; Petit et al., 2011) by both increasing the size of aggregates (Allen and Smith, 2001; Schmitt et al., 2007) and lowering the BLG denaturation temperature, which in turn, favours aggregate formation (De Wit, 1990; Simmons et al., 2007). Its role in BLG unfolding is limited to the reinforcement of the native BLG tertiary structure (Petit et al., 2011). However, it has been demonstrated that the role of Ca^{2+} in the formation of intermolecular bridges is unlikely (Xiong et al., 1993), and its action was limited to screening BLG surface charges (Simons et al., 2002).

Interestingly, Phan-Xuan et al. (2013) reported that a critical molar ratio of calcium to protein (noted R) is needed to permit microgel formation. These are independent of the protein concentration for pH $\geqslant$ 6.9. At $R < 1$, aggregates have the form of small curved strands, whilst at higher ratios, larger spherical particles are formed. The critical ratio increases only slightly with decreasing heating temperature from 1–1.5 at 85 °C to 2–2.5 at 70 °C. The microgel suspensions are stable in a narrow range of R, although aggregating at higher calcium concentrations.

Alternatively, it has been shown that the deposit consists of both protein and calcium particles aggregates. This protein is present on the surface, as well as in steel defects and inside the grain boundaries. However, the calcium ions are mostly concentrated in the upper side of the grain boundaries (Jimenez et al., 2013).

Although the residence time within the heat exchanger would have an effect on the thermal denaturation kinetics of BLG, data concerning the effect of the flow regime upon the fouling behaviour for long duration experiments (i.e. Reynolds numbers or shear stress values) are scarce. The only work that gives detailed results on the effect of the Reynolds number on fouling by WPC in a THE is that of Belmar-Beiny et al. (1993) for a fouling run of an hour. They showed that the higher the Reynolds number (in the range 2000–7000) the smaller the deposit, which decreased steadily, even with a shear rate lower than those encountered in PHE.

There is therefore a lack of data whether confirmed or controversial concerning the dependence of the deposit fouling structure on the calcium content of the fouling fluid or on the Reynolds number in a PHE. To fill the gap, the effect of both the calcium content (70–87.5 mg L^{-1} corresponding to R ranging from 6.8 to 8.5) and the Reynolds number on fouling, with a WPC solution as a model fluid, was investigated. WPC was chosen because it is widely used as a functional food ingredient in food products. Consequently, it constitutes a good model for other milk-based products. The experimental fouling study was performed using a whey protein concentrate in a well-defined geometry, namely a plate heat exchanger, for 330 min. In addition, cleaning trials were performed to investigate the effect of the deposit structure on the cleaning process.

2. Materials and methods

2.1. Fouling fluid

Whey protein powder from sweet whey (WPC 75, Armor Proteines, France) dissolved in controlled-quality water (1% w/w), was used as the model fluid. The composition of the WPC powder was mainly proteins (75% w/w), in which BLG and alpha-lactalbumin represented 63% and 11% respectively, and lactose (10% w/w).