Comparison of the mechanical properties of milk fouling and whey protein fouling

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The formation of fouling deposit is a significant problem for the dairy industry. Many experimental analyses have been carried out to explore the cleaning process using whey protein solution as a surrogate material because the main fouling components in milk are whey proteins. In view of mechanical cleaning processes, the mechanical behaviour of milk and whey protein fouling is compared using indentation and relaxation experiments and material parameters of a visco-hyperelastic model are determined using an inverse finite element method (FEM).

1 Introduction

To purge the fouling deposits forming rapidly on the surface of the heating equipment during pasteurisation and sterilisation, Cleaning in Place (CIP) has become increasingly relevant for the dairy industry due to its reduced cleaning time. It can be realised by spraying or circulating cleaning solutions with a certain temperature and flow velocity. CIP has been investigated in much detail to find an appropriate combination of thermal, chemical and mechanical forces and to improve cleaning efficiency. In order to achieve a comprehensive understanding of fouling formation and the complicated interplay of the three influencing factors, reconstituted whey protein concentrate (WPC) and whey protein isolate (WPI) were used as substitute materials in many experimental studies due to their heat sensitivity and the important role of heat-induced denaturation of milk. In spite of the mechanisms of fouling formation, there is still a large lack of understanding of the mechanical properties of milk fouling and its impact on CIP. Therefore, the aim of this work is to compare the mechanical properties of milk fouling and whey protein fouling.

2 Material and methods

2.1 Fouling experiment

Fouling experiments were carried out in a double jacket tank following [1]. About 2.5 L process fluid was heated up to a bulk temperature of 40 °C and was stirred by an impeller to avoid large shear agitation and gas entrainment. As process fluids, raw milk and WPI solutions with different concentrations ranging from 0.1 g/L to 55 g/L were used to generate the appropriate fouling deposits. Four steel plates (5 × 20 × 2 mm) for accumulating the fouling deposits together with two filling plates resulting in an overall size of 80 × 20 × 2 mm were clamped onto a square tube heating element with an electrical cartridge heater and immersed in the tempered process fluid. All the fouling experiments were conducted with a constant heat flux of 160 W.

2.2 Mechanical experiment

Indentation experiments were carried out to investigate the local mechanical properties of the fouling layer. The steel plate with accumulated fouling deposit was glued to a holder, which was screwed onto a micro-manipulator embedded in an inverted microscope. A short glass fibre (Ø = 275 μm) was glued to a force sensor as indenter to measure forces. The force sensor was fixed on the microscope and the gripped fouling plate was moved against the force sensor. For the preloading, once the glass fibre was sufficiently close to the fouling layer, the plate was driven slowly until a little deformation of the fouling could be observed in the microscope combined with an increasing force recorded by the micro-force sensor. For the indentation test, a loading rate of 1μm/s was used up to a strain of ε = 40 %. For the relaxation test, ε = 40 % was reached within 18 seconds and the indenter was then held fixed to allow for a decrease in stress.

2.3 Inverse analyses

Inverse FEM (iFEM) was carried out using the finite element software Abaqus/CAE 2018 (Dassault Systèmes, Simulia Corp.) coupled with Matlabs® R2017a (The MathWorks, Inc.) through a differential evolution algorithm [2]. Under the assumption

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of incompressibility, a two-term reduced polynomial model was chosen to describe the non-linear force-strain behaviour of the fouling [3], whose strain energy function

\[ W(C_{10}, C_{20}) = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 \]  

depends on the first invariant \( I_1 \) and the material constants \( C_{10} \) and \( C_{20} \). To take time dependence into account, the hyperelastic model was augmented by a three-term Prony series. To simulate the mechanical tests, an axisymmetric model was set up with an analytical rigid flat punch as the indenter and a simplified cylinder (\( \Omega = 2 \text{ mm} \)) as the fouling. As a measure of the agreement between simulated and experimental results, an objective function \( O_{\text{tot}}(p) \) is introduced, which encompasses the relative error norms \( O_{\text{ind}}(p) \) and \( O_{\text{rel}}(p) \) for the agreement of indentation and relaxation tests, respectively.

### 3 Results and Discussion

Despite the complex geometry and small thickness, indentation tests can be used to investigate the local mechanical behaviour of the fouling deposits. Milk fouling is a soft material showing a strongly non-linear force-strain relation. The results of the indentation tests on WPI fouling generated from WPI solutions with different concentrations indicate a relation between stiffness and concentration. The measured forces increase with the concentration of the WPI solution. For a concentration of 0.1 g/L, the WPI fouling behaves mechanically similar to milk fouling in both material tests.

Based on the mean experimental forces, the parameters of milk fouling determined through inverse FEM are listed in Table 1 and the corresponding curves are displayed in Figures 1 (c) and (d). The curves in both simulations and the values of all the objective functions show a good agreement between the experimental and simulated results. The value of \( C_{20} \) is higher than \( C_{10} \), which implies a non-linear increase at large strain and also further corroborates the non-linear material behaviour. According to the Prony series parameters \( g_1, g_2, g_3 \) in Table 1, the dimensionless long term modulus is \( 1 - g_1 - g_2 - g_3 = 0.1 \), which is smaller than the value observed from the force-strain curve. The difference between the long term dimensionless modulus of the normalised curve and the results from iFEM might be due to the large local deformation near the indenter. Owing to the assumption of incompressibility, the material underneath the indenter is displaced sideways. During stress relaxation, this deformation entails a local elongation, which is much larger than the imposed macroscopic strain of \( \varepsilon = 40 \% \). This effect can be reduced by a decreasing the long term dimensionless modulus. The influence of minerals in the WPI solution on the mechanical behaviour of fouling will be considered in future work, which may render the formation of WPI fouling closer to real milk fouling. Additionally, a numerical approach will be pursued to investigate the propagation of cracks inside the fouling layer and to obtain a more thorough understanding of the mechanical cleaning mechanisms for CIP.

Acknowledgements Partial support for this research was provided by the Deutsche Forschungsgemeinschaft (DFG) under Grant BO 3091/21-1.

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