Rheology of Commercial and Model Ice Creams

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Received: 3.5.2007, Final version: 29.6.2007

Abstract:
The rheologies of a shear-frozen commercial ice cream and of a model ice cream foam have been studied at - 5°C and other temperatures by capillary rheometry on a commercial manufacturing line and in a Multi-Pass Rheometer, respectively. Both were 50 vol% aerated emulsions of milk fat in an aqueous sucrose solution, but the model ice cream foam was without ice crystals. The data indicate significant wall slip effects which have been analysed using the classical Mooney method, the Jastrzebski variant and one based on Tikhonov regularization. The latter approach yields 'most convincing results', including a previously unreported region of shear thickening at very high shear rates of ~ 3000 s^{-1} for the model ice cream foam, when the capillary number indicates a possible transition in the flow around bubbles from domination by interfacial effects to viscous effects. Viscous heating effects were observed at relatively low shear rates for the commercial ice cream, but not the model ice cream foam. This was attributed to the melting of the ice crystal phase in the commercial ice cream, and, hence, absent from the model ice cream foam.

Zusammenfassung:
Gegenstand der Untersuchung war die Rheologie von scher-gefrorenem kommerziellem Speiseeis sowie eines Modell-Eiscremeschaums bei Temperaturen von - 5°C und darunter. Zur Anwendung kamen kapillare Rheometrie einer kommerziellen Produktionsstrecke sowie ein Multi-Pass-Rheometer. In beiden Fällen handelte es sich um eine Emulsion aus Milch, Fett und Zucker-Wasserlösung mit einem Luftanteil von 50%; der Modell-Eiscremeschaum war jedoch frei von Eiskristallen. Die Daten deuteten auf signifikante Slipeffekte an der Wand hin und wurden mit Hilfe der klassichen Mooney-Methode, der Jastrzebski-Variante sowie einer auf der Tikhonov-Regelung basierenden Methode untersucht. Letztere lieferte die 'überzeugendsten Ergebnisse', auch bei der bislang noch nicht untersuchten Scher-Eindickung bei sehr hohen Scherraten von 3000 s^{-1} für den Modell-Eiscremeschaum. In dem vorliegenden Kapillarzahlenbereich bestand die Möglichkeit eines Überganges von grenzflächendominierter zu viskosdominierter Blasenumströmung. Viskose Erwärmungseffekte wurden bei kommerzieller Eiscreme bereits bei geringen Scherraten beobachtet, nicht jedoch beim Modell-Eiscremeschaum. Dieses wurde dem Schmelzen der Eisphase der kommerziellen Eiscreme zugeschrieben.

Résumé:
Les comportements rhéologiques d'une crème glacée (congelée sous cisaillement) ainsi que d'une mousse (échantillon modèle de la crème glacée dépourvu de cristaux de glace) ont été étudiés respectivement à - 5°C par un rhéomètre à capillaire sur une chaîne de production et par un MPR („Multi-Pass Rheometer“). Chaque échantillon, décrit ci-dessus, consiste en une émulsion lipidique (issue du lait) dispersée dans une solution de sucrose aérée à 50% de son volume. A cette température, seule le modèle de la crème glacée (mousse) ne contient pas de cristaux de glace. Les résultats rhéologiques indiquent de forts glissements à la paroi qui ont été analysés par la méthode classique de Mooney, la variante de Jastrzebski ainsi que d´une méthode basée sue la régularisation de Tikhonov. Cette dernière approche conduit à des résultats convaincants pour le modèle de la crème glacée, jusqu'alors jamais reportés. Ils présentent une région d'épaississement au cours de cisaillements pouvant atteindre 3000 s^{-1}. Ce phénomène a été interprété par le „capillary number“, qui indique une potentielle transition d'un écoulement d'interfaces à un écoulement dominant visqueux autour des bulles d'air de la mousse. A faible niveau de cisaillement, des échauffements visqueux ont été observés pour la crème glacée mais pas pour le modèle de la crème glacée; ceci est dû à la fonte des cristaux de glace de la crème glacée absents de la solution modèle aérée.

Key words: bubbles, flow, foam, ice cream, rheology, wall slip

© Appl. Rheol. 18 (2008) 12913-1 – 12913-11

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3.3 COMPARISON OF MANUFACTURING LINE TO LABORATORY RESULTS

The increased control of experimental conditions in the laboratory enabled a more detailed analysis of the model foam to be made than was possible for the ice cream on the manufacturing line. However it is difficult to reproduce the continuous production stream of frozen ice cream in the laboratory, which leads to the use of more ideal, but less realistic, model materials.

The TRM characterization of the model foam in Figures 3 and 9 (with ϕ = 0.50 ± 0.15 and T_c = - 5.0 ± 0.1°C) was used to predict the model foam flow curves within the pipe geometries used on the manufacturing line (with ϕ = 0.11 ± 0.01, T_c = - 5.6 ± 0.3°C). The resulting model flow foam curves are included on Figure 2. This illustrates how aerating the model foam matrix with air bubbles has given it a yield stress, leading to plug flow for all wall shear stresses below 1.42 Pa. There is approximate agreement with the ice cream and the model foam below this yield stress. However the ice cream appears to have a higher yield stress, in excess of 2.5 kPa, which is to be expected since it contains ice crystals and has a lower voidage.

There is very good agreement between the TRM wall slip velocity and wall shear stress fits for the ice cream and model foam, shown in Figure 3. This is consistent with a high shear slip layer next to the pipe wall consisting primarily of the liquid matrix alone, the liquid phases in both cases having similar compositions.

The model foam did not appear to display any of the effects of viscous heating which were apparent in the ice cream, even at very high shear rates. This may be due to various differences between the systems, but the removal of ice phase volume due to melting from the foam is expected to be a key factor. The ice fraction of frozen standard vanilla ice cream has been measured to vary from 16 to 40 % as temperature was reduced just 2°C from - 3 to - 5°C[3].

4 CONCLUSION

The rheologies of a commercial ice cream and a model ice cream foam have been studied using capillary rheometry on a manufacturing line and in a laboratory using the Multi-Pass Rheometer respectively. Slip analysis of the flow data was performed using three methods; the classical Mooney method, the Jastrzebski Mooney method and the Tikhonov regularization Mooney method. Tikhonov regularization was found to be the superior method of analysis. The Jastrzebski Mooney method was shown to produce a significantly different interpretation of the flow, and due to the lack of a physical basis or any evidence of its validity it is recommended that in the absence of further support this method is not used for foam slip determination.

The commercial ice cream was shown to display both wall slip and viscous heating effects. It displayed a yield stress under certain conditions, and a power-law relationship under others; these suggest that a temperature dependent Herschel-Bulkley model would be appropriate, although further study of these is required to obtain a complete characterization.

The model ice cream foam flow passes from interfacial dominated behaviour at low shear stresses to viscous dominated behaviour at high shear stresses. The respective foam viscosities were greater than and less than the apparent viscosity of the liquid matrix. A period of shear thickening was observed which has not been previously reported in the literature, but as yet explanations of it are speculative.

ACKNOWLEDGEMENTS

Permission from Unilever to publish the experimental data is gratefully acknowledged. Prof. Malcolm Mackley and Dr. Simon Butler at Cambridge, Dr. Deryck Cebula at Unilever and Dr. Paul Grassia at The University of Manchester are acknowledged and thanked for their input. Jean-Yves Mugnier at Unilever conducted the microscopy.

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