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Modelling the properties of liquid foods for use of process flowsheeting simulators: Application to milk concentration

Martial Madoumier [a,b], Catherine Azzaro-Pantel [c,*], Gaëlle Tanguy [a,b], Geneviève Gésan-Guiziou [a,b,*]

[a] INRA, UMR1253 Science et Technologie du Lait et de l'Œuf, 65 rue de Saint Brieuc, 35000 Rennes, France
[b] AGROCAMPUS OUEST, UMR1253 Science et Technologie du Lait et de l'Œuf, 65 rue de Saint Brieuc, 35000 Rennes, France
[c] Laboratoire de Génie Chimique, UMR5503 CNRS, Université de Toulouse, ENSIACET INPT/UPS, BP 84234, F-31432 Toulouse, France

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ABSTRACT

In this paper, a modelling approach for liquid food products in a chemical process simulator is proposed from the flowsheeting methodology widely used for chemical processes. The focus is set on dairy concentration processes, in which milk is defined as a mixture of water and four dry matter components (fat, proteins, carbohydrates, minerals) modelled as "pseudo-components" in a conventional simulator which has been adapted to take into account the behaviour of the liquid food product considered. The significant properties of milk (heat capacity, boiling point elevation, thermal conductivity, density, viscosity, surface tension) are modelled with empirical models found in the literature and implemented in the simulator. In order to validate the approach, an industrial milk evaporation process and a pilot-scale evaporator are modelled and simulated. The results are compared with industrial and experimental results respectively, and show a good agreement with the industrial process. However improvements are needed in modelling the pilot scale evaporator. The proposed approach is generic enough to be extended to other liquid foods.

1. Introduction

The design and development of sustainable food processes, which integrate technical and economic criteria, satisfy customer demands, and are less harmful to ecosystems, constitute a major challenge in a context of global changes (climate change, energy scarcity and energy price increase). An interesting way to meet these constraints entails a systematic approach combining process modelling, simulation, and process optimisation (Azapagic et al., 2011; Lam et al., 2011).

It is recognized that the chemical and petroleum industries are quite familiar with the simulation–optimisation approach, and widely use process simulators such as Aspen Plus, Aspen Hysys, ProSimPlus, Pro/II, and COCO to compute mass and energy balances. These powerful software tools are based on the modelling of heat and mass transfers inside unit operations and their interconnection, by using thermodynamic databases. The use of process simulators then requires the exact knowledge of the composition of the fluids, the specific properties of the individual components and of the involved mixtures, for which changes in the physico-chemical properties of the product through unit operations are computed.

Despite the proximity of the chemical and petroleum sectors with the food industry, the development of this approach in the food sector suffers from two major shortcomings, i.e. a lack of available and applicable food process models (Trystram, 2012), and a lack of thermodynamic models that account for the complexity and biological variations of food materials (Carson, 2006; Fito et al., 2007; Lambert et al., 2013). Thermodynamic models, that allow a complete understanding of molecular behaviour and a prediction of physical properties of a mixture, are only known for specific mixtures such as those classically encountered in the chemical industry. They are not available for food products for which the composition is very complex (more than 2000 molecules in milk for instance) and their properties depend on both the concentration of their components and the interaction between them.

Several attempts at modelling liquid food properties have been achieved so that process simulators and other software tools can be used. Table 1 shows some significant studies which deal with the modelling and simulation of liquid food processes, with an emphasis on fluid milk. Two main approaches are proposed (Table 1):

* Corresponding authors at: INRA, UMR1253 Science et Technologie du Lait et de l'Œuf, 65 rue de Saint Brieuc, 35000 Rennes, France (G. Gésan-Guiziou).
E-mail addresses: catherine.azzaropantel@ensiacet.fr (C. Azzaro-Pantel), genevieve.gesan-guiziou@rennes.inra.fr (G. Gésan-Guiziou).

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Nomenclature

A_i	Coefficient specific of component i in the selected viscosity model (see Section 3)	T	Temperature (°C)
BPE	Boiling point elevation (°C)	T_{SAT}	Saturation temperature (°C)
Cp	Specific heat (J g^{-1} K^{-1})	X_i	Mass fraction of component "i" (mass/mass)
DM	Dry matter content (mass%)	x_{SOL}	Total molar fraction of solutes (mol/mol)
H_{vap}	Vaporization enthalpy (J kg^{-1})	ρ	Density (kg m^{-3})
MW	Molecular weight (g mol^{-1})	λ	Thermal conductivity (W m^{-1} K^{-1})
R	Mass gas constant (J g^{-1} K^{-1})	μ	Dynamic viscosity (mPa s)
TEMA	Tubular Exchanger Manufacturers Association	σ	Surface tension (mN m^{-1})

Table 1
Liquid food properties models used in chemical process simulators (and other software Tools).

	Reference	Food unit operations modelled	Food type & definition	Software (company)	Origin of the data to compare the simulation with	Limits to usability in this study
Unique component approach	Ribeiro (2001) and Ribeiro and Andrade (2003)	Preheating, pasteurization, evaporation	Milk (non-conventional unique component)	Aspen Plus (AspenTech) with Fortran 77 unit operation models	Industrial data	Unit operation models include milk properties in their code
	Bon et al. (2010)	Pasteurization	Whole milk	ProSimPlus (ProSim)	Theoretical process	No concentration involved
	Jorge et al. (2010)	Evaporation	Sugarcane juice	Aspen HYSYS (AspenTech)	Industrial data	Unit operation models include sugarcane properties in their code
Pseudo-component approach	Diefes (1997)	Evaporation, spray drying, ultrafiltration, heat exchanger, pumping, holding	Milk: water, fat, proteins, carbohydrates, ash	Matlab with Simulink (MathWorks)	Theoretical processes	Simulator developed internally
	Chawankul et al. (2001)	Evaporation	Orange juice: water, dry component	Aspen Plus (AspenTech)	Experimental data from laboratory and plant scales	Heat transfer coefficient models includes empirical property models; undocumented modelling in streams
	Miranda and Simpson (2005)	Evaporation	Tomato juice: water, dry component	Undocumented	Industrial data	Simulator developed internally
	Cheng and Friis (2007)	Fat standardization, homogenization, pasteurization, cooling	Milk: water, fat, proteins, carbohydrates, ash	Pro/II (Invensys)	Theoretical process	No concentration involved
	Skoglund (2007)	Pasteurization, sterilization, homogenization, pumping, storage	Milk: water, fat, proteins, carbohydrates, ash	Modelica with Dymola (Dassault Systemes)	Industrial data	No concentration involved; simulator developed internally (Commercial library of models)
	Byluppala (2010)	Evaporation, settling, extraction	Milk: water, lactose, 12 fatty acids	Aspen Plus (AspenTech)	No validation because no experimental data was available in the literature	Modelling of chemical interactions is required to simulate the extraction process
Undefined approach	Tomasula et al. (2013)	Homogenization, storage, preheating, pasteurization, holding, fat standardization, homogenization, cooling	Undocumented	SuperPro Designer (Intelligen Inc.)	Theoretical process	No concentration involved; undocumented milk properties

- The food product is defined as a new component ("Unique component approach", see Table 1). This approach is the simplest one, since the properties of the food product are specified as constant or simply depend on temperature, which can be useful to the simulation of the heating or cooling of food product, or to any process step where there is no change in the composition. This last point constitutes one of the two major disadvantages of this approach: (i) it makes it impossible to predict changes in physico-chemical properties in the case of a new composition of the feed (e.g. more fat in the case of milk); (ii) it cannot predict the performance of a process versus a change in properties due to the variation of the composition of the fluid (e.g. concentration) without modifying the built-in unit operation models of the simulator. Bon et al. (2010) successfully modelled and optimised a pasteurization process by defining milk as a single component. Conversely Ribeiro (2001) and Jorge et al. (2010) tried to use this approach to model milk for a concentration step (where one component (water) is partially removed from the treated product) but in these cases the development of new unit operation models was necessary to account for product concentration in the process simulators.