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Virtual milk for modelling and simulation of dairy processes

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ABSTRACT

The modeling of dairy processing using a generic process simulator suffers from shortcomings, given that many simulators do not contain milk components in their component libraries. Recently, pseudo-milk components for a commercial process simulator were proposed for simulation and the current work extends this pseudo-milk concept by studying the effect of both total milk solids and temperature on key physical properties such as thermal conductivity, density, viscosity, and heat capacity. This paper also uses expanded fluid and power law models to predict milk viscosity over the temperature range from 4 to 75°C and develops a succinct regressed model for heat capacity as a function of temperature and fat composition. The pseudo-milk was validated by comparing the simulated and actual values of the physical properties of milk. The milk thermal conductivity, density, viscosity, and heat capacity showed differences of less than 2, 4, 3, and 1.5%, respectively, between the simulated results and actual values. This work extends the capabilities of the previously proposed pseudo-milk and of a process simulator to model dairy processes, processing different types of milk (e.g., whole milk, skim milk, and concentrated milk) with different intrinsic compositions, and to predict correct material and energy balances for dairy processes.
Key words: process simulation, milk processing, thermal conductivity, viscosity, heat capacity

INTRODUCTION

Modeling and simulation of industrial processes are useful to predict process behavior and critical for decision making and optimization without putting the real process at risk. Process simulation significantly contributes to analyzing process operation, performance, and process or product variable trends with reasonably acceptable accuracies (Munir et al., 2012b). Commercial process simulators (such as VMGSim; Virtual Materials Group Inc., Calgary, AB, Canada) are usually preferred over self-developed numerical modeling tools because commercial simulators typically include substantial component libraries, advanced computational methods, comprehensive thermodynamic packages, user-friendly graphical user interfaces (GUI), process flow sheet visualization, and pre-made major unit operations. The simulators have also been validated over many years with large critical user bases (Munir et al., 2013).

Although common in many processing industries, the simulation of dairy processing using commercial process simulators has lagged behind largely because the historical market for most process simulators is chemical or petrochemical applications (Arthur et al., 2014). Other reasons for the slow uptake of process simulation in the dairy industry include the fact that milk is a complex food structure with complex irreversible property changes, multiple phases, and, most importantly, the nonavailability of dairy components in the component libraries of process simulator (Wang and Hirai, 2011; Trystram, 2012; Tajammal Munir et al., 2015). This paper aims to rectify this omission by showing how milk can be considered a mixture of known compounds such that the thermodynamic package of the process simulator can estimate the key physical properties of milk under a variety of processing conditions.

Dairy processing modeling case studies are rare. Tomasula et al. (2013) used SuperPro Designer (Intelligen Inc., Scotch Plains, NJ) to develop a simulation tool for the fluid milk industry, whereas Abakarov and Nuñez (2012) discussed the available food engineering software without actually considering modern process simulator capabilities. Bon et al. (2010) presented the use and capabilities of ProSimPlus (Philadelphia, PA) for milk pasteurization process modeling, and Madoumier et al. (2015) proposed a new modeling approach for liquid foods in a process simulator.

The key differences between Bon et al. (2010), Madoumier et al. (2015), and the present study are outlined in Table 1. In the present study, milk was con-

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sidered a "mixture" of water and pseudo-components. Madoumier et al. (2015) followed a similar approach. In contrast, Bon et al. (2010) considered milk as a single pseudo-component but this approach has some drawbacks. For example, such an approach has limited applications when the different components of milk are separated, such as in ultrafiltration, and it is not possible to vary the total solids (TS) such as in powder processes. Finally, we cannot model the influence of different operating conditions on milk mixture components; for example, behavior of milk fat is different from that of milk proteins under the same operating conditions.

There are 2 major differences between Madoumier et al. (2015) and the present study, which are shown in Table 1. The first difference is that milk proteins were modeled differently in the current study and in Madoumier et al. (2015). Madoumier et al. (2015) ignored 20% (by weight) of the proteins; namely, whey proteins, and considered only casein proteins. However, whey proteins are essential (e.g., for whey milk or "muscle milk"). The influence of heat treatment on both types of milk protein is also different because casein proteins are stable to heat treatment whereas whey proteins are not. Consequently, milk heat treatment processes cannot be modeled without modeling both whey and casein proteins. Furthermore, the denaturation of both proteins is different. The second major difference is that the viscosity of milk with higher TS seems to be an unsolved issue due to non-Newtonian flow behavior in Madoumier et al. (2015). This flow behavior was modeled in the present study.

Process simulation of dairy processing using commercial process simulators involves several specific steps. Regardless of the type of problem and the objective of the simulation, the first basic step is selecting components or mixtures that will be involved in the simulation from the simulator's component library (Luyben, 2002; Seborg et al., 2004; Munir et al., 2012a). Although milk is technically a colloidal suspension, process simulators use the term "mixture" or "pseudo-mixture" in this instance. The main components of milk are water, fats, proteins, lactose, and minerals, all compounds that are uncommon or unavailable in most commercial component libraries.

Primarily, 2 different modeling approaches for milk modeling have been attempted. Ribeiro and Andrade (2003) and Ribeiro and Caño Andrade (2002) used a unique component approach for milk modeling, whereas Zhang et al. (2015) and Tomasula et al. (2014) opted for a pseudo-milk component approach. The unique component milk modeling approach is simpler because the milk component properties are specified as constant or depending only on temperature. Such a modeling ap-

Table 1. Key differences between Bon et al. (2010), Madoumier et al. (2015), and the present work

Key difference	Bon et al. (2010)	Madoumier et al. (2015)	Present study
Milk as a raw material	Milk was considered as a single pseudo-component.	Milk was considered as a milk "mixture" following methodology proposed in authors' previous work (Zhang et al., 2015).	Milk was considered as a milk "mixture."
Applications	Limited to milk pasteurization processes only.	Seems applicable to most dairy processes except milk heat treatment.	Applicable to most of dairy processes including heat treatment processes.
Types of milk	Only whole milk was considered.	Whole and skim milks with different dry matter were considered.	Different types of milk (e.g., whole, skim, and concentrated) were considered.
Influence of operating conditions	The influence of temperature alone on the physical properties of milk was studied.	The influence of different operating conditions on the physical properties of milk was studied.	The influence of temperature and different solid concentrations on the physical properties of milk was studied.
Whey proteins	Whey proteins were ignored.	Whey proteins were ignored.	Whey proteins were considered to evaluate the influence of heat treatment on milk proteins.
Viscosity	The viscosity of milk with higher total solids was not considered.	The viscosity of milk with higher total solids seems an unsolved issue due to non-Newtonian flow behavior.	Expanded fluid and power law models were used to predict non-Newtonian flow behavior of concentrated milk viscosity.
Heat capacity	The heat capacity of milk with higher total solids was not studied.	The heat capacity of milk with higher fat concentrations seems an unsolved problem.	An expression for the heat capacity as a function of temperature and fat content was postulated to capture the double Gaussian peaks.