Steady State modeling of milk evaporation process using a commercial process simulator

김윤수, 김도현[1], Brent R. Young[2, *], Wei Yu[3,]
한국과학기술원, [1]한국과학기술원, [2]University of Auckland, [3]University of Auckland
(b.young@auckland.ac.nz[*])

Yunsu Kim, Do hyun Kim[1], Brent R. Young[2,*], Wei Yu[3]
KAIST, [1]KAIST, [2]University of Auckland, [3]University of Auckland
(b.young@auckland.ac.nz[*])

Abstract

Modeling and simulation is very important to understand the relationships between process variables and product quality using a variety of computer-aided tools in chemical and pharmaceutical industries. The objective of this research was to test the capability of a commercial process simulator for the steady-state modeling of dairy processing. Steady-state model of a whole milk evaporation process was built using a commercial process simulator. The thermo-physical properties of the milk were defined in terms of simple linear polynomial functions. Pseudo-milk was constructed with existing compounds in the simulator and artificial compounds. Seven stages multiple effect evaporator was developed to simulate steady state model in the process simulator. The model was validated against literature and industry data. The results showed that the model can provide reliable information of the thermo-physical properties of the milk in the evaporator. It was concluded that steady state model of whole milk evaporation process can be simulated using a commercial process simulator.

Keywords: - milk evaporation process, steady state modeling.

I. Introduction

Modeling and simulation is very important to understand the relationships between process variables and product quality using a variety of computer-aided tools in chemical industries. One of the challenges is to investigate the correlations between process variables and physical properties of the milk in dairy process streams. Therefore, building a milk process simulation model is a fundamental task to understand process variables and the properties of the milk. It predicts contribution of each process variable's effect on the physical properties of the milk. It also helps to achieve better process control for regulating the amounts of each process variable during milk process, and for better product quality with lower costs.

Milk evaporation process is very important in dairy industry for reducing the cost of drying, storage and transportation. To lower steam requirement, the evaporation unit is normally designed as a multiple-effect evaporator. Seven stages multiple-effect evaporator operates at progressively lower pressures and thus lower boiling points. The dairy industry generally uses falling film evaporator to design the multiple-effect evaporators. The schematic diagram of falling film evaporator is shown in Figure 1.

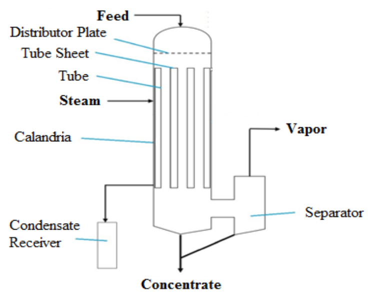

Figure 1: Falling film evaporator

In order to develop a simulation model of the milk evaporation process, milk physical properties such as heat capacity, mass density, viscosity and thermal conductivity should be determined. Based on these properties, it is possible to determine the rate of heat transfer in evaporation and other heating process. In addition, optimization and precise control of several processing unit operations such as pump, heater, cooler, dryer, etc. can also be achieved.

The objective of this research was to test the capability of a commercial process simulator the steady-state modeling of dairy processing. A commercial process simulator called VMGSIM (Version 6.5, 2012) was used in this research project. VMGSim is commonly used in the field of oil and gas processing and it was used to test whether the simulator can be used for dairy process simulation.

This paper is organized as follows. After this general introduction, theory and experiment used in this study is described in section II and III. In section IV results are discussed. Finally conclusion is drawn in section V.

II. Theory

Chen [1] and Rahman [2] mentioned that the most important physical properties of the food liquids for evaporation process are the mass density, viscosity, thermal conductivity, and specific heat capacity. Only fewer public literatures described the thermo-physical properties of raw milk. Also there were limited time and resources available to examine the properties of raw milk in a pilot plant scale. To figure out this problem, the linear polynomial equations developed by Minim et al, and Fernandez-Martin were used to define the mass density, specific heat capacity, thermal conductivity, and viscosity properties of the raw milk. The thermo-physical properties of the real raw milk might be slightly different to the properties described by their studies because their studies were based on the whole milk, skimmed milk and partially skimmed milk. Therefore it was assumed that the thermo-physical properties of the raw milk in this study had the same properties of whole milk.

The thermal conductivity, heat capacity, mass density of the whole milk, skimmed milk, and partially skimmed milk were studied previously by Minim et al [3]; the experiments were designed to examine the influence of temperature, water content, and fat content on mass density, heat capacity, and thermal conductivity of the milks. The following equations are the simple linear polynomial expressions of thermal conductivity, heat capacity, and density of milk, based on their experiment results;

$$\rho = 1185.64 - 0.341T - 58.239W_w - 58.107W_f \quad (1)$$

$$C_p = 1.4017 + 0.0021T - 2.1816W_w - 1.7430W_f \quad (2)$$

$$k = -0.2154 + 0.0014T + 0.4171W_w - 0.0942W_f \quad (3)$$

where ρ is the mass density in $kg \cdot m^{-3}$, T is the temperature in K, W_w is the mass fraction of water, and W_f is the mass fraction of fat.

Fernandez-Martin [4] investigated the influence of temperature and composition on viscosity of milk and milk concentrates. The general expression of dynamic viscosity coefficients with temperature and total solid content was;

$$\log \eta = 0.2490 - 0.0130T + 0.000052T^2 + (0.02549 - 0.000098T + 0.00000040T^2)s + (0.000543 - 0.0000139T + 0.000000117T^2)s^2 \quad (4)$$

Where η is the dynamic viscosity in cp, T is the temperature in °C, s is the total solid content (% w/w)

When the temperature, water content, fat content and total solid content in milk are defined, it is possible to predict the thermo-physical properties of the milk.

III. Experiment

A pseudo-milk component was proposed by Zhang et al [5]. In this paper another pseudo-milk settings were made for the evaporation modeling. The minor components such as minerals of the milk were excluded in this study. The major milk components selected in this study were water, fats (oleic acid and n-hexadecanoic acid), lactose, and proteins. Advanced Peng-Robinson thermodynamic model was chosen as the property package in this paper because the model can accurately and easily represent the relation among temperature, pressure, and phase compositions in multi-component systems.

	Molecular formula	CAS number	Molar mass	Boiling point	Density
Lactose	C12H22O11	63-42-3	342.30g/mol	668.9°C	1.525g/cm^3

Table 1: Lactose physical properties [6].

The main components of fat in milk are palmitic acid and oleic acid. The physical properties of palmitic acid are not easily available in literature. Therefore, n-hexadecanoic acid from the simulator component library was selected to represent palmitic acid, since they have relatively similar thermo-physical properties. The oleic acid component was also selected from the simulator component library. Lactose compound was hypothetically generated using hypothetical compound functions. Table 1 shows the lactose properties used in the simulator. The main proteins in milk were Alpha S1, Alpha S2, Beta, and Kappa casein molecules [7]. The average molecular mass of the caseins was estimated and used to represent total protein component in the raw milk. The unknown specific heat capacity, mass density, viscosity, and thermal conductivity of the protein components were manually set by using the polynomial regression; the coefficients on the polynomial regression function of each thermo-physical property were manually iterated until the thermo-physical property values of raw milk in the simulator closely matched to the thermo-physical property patterns described by Equations (1) to (4) with temperature range from 275 to 353K.

The raw pseudo-milk created in the simulator was set to the following compositions: 87.1% water, 2.2% oleic acid, 1.7% n-hexadecanoic acid, 4.8% lactose, and 4.2% total proteins. The oleic acid and n-hexadecanoic acid represents 3.9% total fat content in the milk.

The pseudo-milk was passed through the calandria of the evaporators shown in Figure 2. The seven evaporators were built as lumped model to simulate the vaporization and separation of water from pre-heated milk in the evaporator. This lumped evaporator units helped to find out the amounts of energy required to evaporate the milk and to estimate the specification of physical condition in the seven stages multiple-effect evaporator and the evaporated milk quality. In addition, it will help to predict and control the specification of evaporated milk at the end. The energy required to heat the milk in the first evaporator was generated from the steam in the cooling section of the first evaporator.

IV. Results and discussion

1) Validation against literature data

Table 1 shows the results and the comparison with the expected values from the literature. Morison and Hartell [8] mentioned that typical operating conditions for falling film evaporators in the dairy industry. The range of operating temperature is between 45°C and 70°C. In the

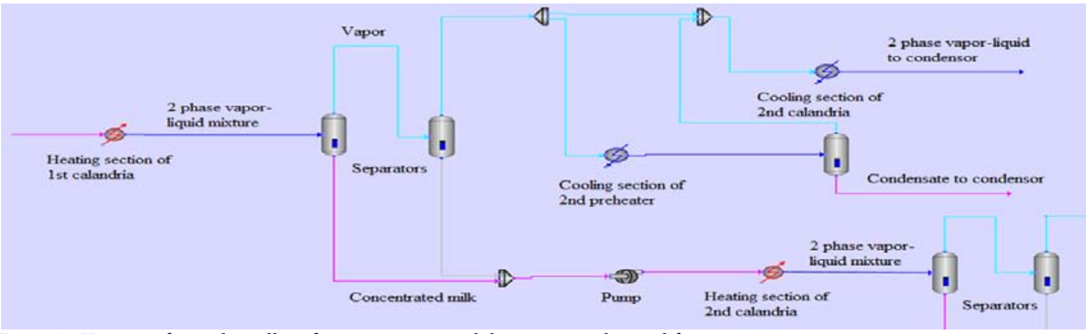

Figure 2: Heating of pseudo-milk in first evaporator with heat energy obtained from steam

Table 1. Comparison of temperature, mass density and viscosity of Whole-milk A and Literature.

	1st Calandria	2nd Calandria	3rd Calandria	4th Calandria	5th Calandria	6th Calandria	7th Calandria	Literature
Temperature (°C)	59.3	57.6	55.9	54.2	52.5	50.8	49.1	45~70
Mass Density (kg/m3)	1033	1045	1059	1074	1092	1112	1137	1000~1250
Viscosity (cp)	0.84	0.98	1.2	1.5	1.97	2.69	4.09	0.7~10

simulator modeling it was assumed that heat loss during heat transfer in the evaporator is negligible and there is a uniform heat distribution per area. At 70°C proteins in the milk start to become thermally degraded. The range of the viscosity of liquids processed in evaporators is normally between 0.7 and 10 cp. The range of density of the feed and product is normally between 1000 to 1250kg·m^{-3}.

The operating temperature drop is normally between 2 to 8°C. The information about specific heat capacity, and thermal conductivity in terms of practical aspect could not be found from literature. According to the Table 1, the process simulator model provides very good results for temperature, mass density and viscosity in 1st to 7th calandria, compared to the operating conditions mentioned by Morison and Hartell.

2) Validation against industry data

The comparison results from Figure 3 to 6 showed that the simulator has a capability to simulate the milk evaporation process. To build an accurate model based on industry data, additional information should be obtained. In addition, laboratory experiments are required to fully validate the model by investigating the relationship between the thermo-physical properties of raw milk, whole milk, and evaporated whole milk and temperature.

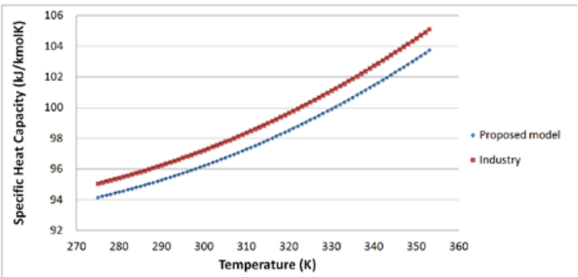

Figure 3: Specific heat capacity values from the proposed model and industrial data

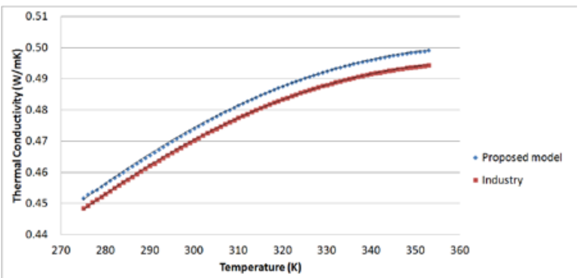

Figure 4: Thermal conductivity values from the proposed model and industrial data

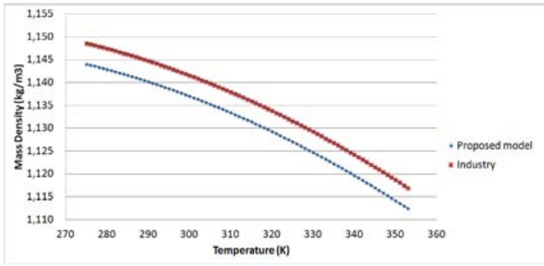

Figure 5: Mass density values from the proposed model and industrial data

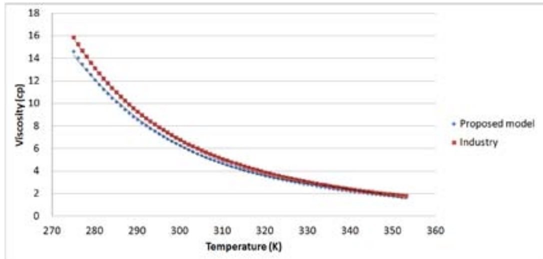

Figure 6: Viscosity values from the proposed model and industrial data

V. Conclusions

The main conclusion from this study is that steady state modeling of evaporation process can be simulated using a commercial process simulator. The validation of the whole milk evaporation model against both literature and industry data showed that commercial process simulator has a capability to simulate the evaporation process. To improve milk evaporation model and to enhance its capability it is recommended to investigate the relationship between the thermo-physical properties of raw milk, whole milk, and evaporated milk and temperature.

References

[1] Chen SC, 1993. "Physicochemical principles for the concentration and freezing of fruit juices". In: Nagy S, Chen CS, Shaw PE, eds, *Fruit Juice Processing Technology*. Agscience, Auburndale, FL.

[2] Rahman S. 1995. *Food Properties Handbook*. CRC Press, New York.

[3] Minim, L. A.; Coimbra, J. S. R.; Minim, V. P. R. "Influence of Temperature and Water and Fat Contents on the Thermophysical Properties of Milk" *J. Chem. Eng. Data* **2002**, 47, 1488-1491.

[4] Fernandez-Martin, F. "Influence of temperature and composition on some physical properties of milk and milk concentrates. II. Viscosity" *J. Dairy Res.* **1971**, 75-82

[5] Zhang Y., Munir, M. T., Yu, W., Young B. R., "Development of hypothetical components for milk process simulation using a commerical process simulator", unpublished

[6] Wikipedia, "Lactose" http://en.wikipedia.org/wiki/Lactose (Wikimedia Foundation, Inc., 2013) (Accessed Jan. 12, 2013)

[7] Yada, R. Y. (2004). "The caseins." *Proteins in food processing*, Woodhead Publishing Limited, Cambridge, 29-62

[8] Morison, K. R., and Hartell, R. W. (2007). Evaporation and Freezing Drying, in Heldman, D. R., and Lund, D. B. eds. Handbook of Food Engineering, 2nd ed, CRC Press, Boca Raton, 495-552.