Modelling of a Falling Film Evaporator for Dairy Processes

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Abstract

The modelling of dairy processing using commercial process simulator lags behind chemical and petrochemical process simulation. This is due to fact that most commercial process simulators do not contain food (e.g. milk) components in their component libraries, required for dairy process simulation. Recently, a “pseudo” milk containing hypothetical components (e.g. milk fat) was developed in a commercial process simulator for milk process simulation (Zhang et al. 2014). In this work, “pseudo” milk was used to model a falling film evaporator used in a milk powder production plant. It shows that commercial process simulators have capability to simulate dairy processes. The model results were validated using both literature and industry data. The model results showed around 0.1 – 9.4% differences between simulated and actual results. This work extends the capabilities of commercial process simulators and can also help practicing engineers to understand potential process improvements.

Keywords: *Process simulation, Evaporator, Pseudo Milk, Milk Powder*.

Introduction

According to Statistics New Zealand 2012 report, New Zealand is processing around 19.5 billion litres/year (BL/yr.) of milk during recent years, making it one of the largest producers of the dairy products. One third of international dairy trade is done by New Zealand every year, accounting for more than 25% of NZ’s export earnings. Figure 1 shows recent growth of dairy and milk productions in New Zealand in recent years.

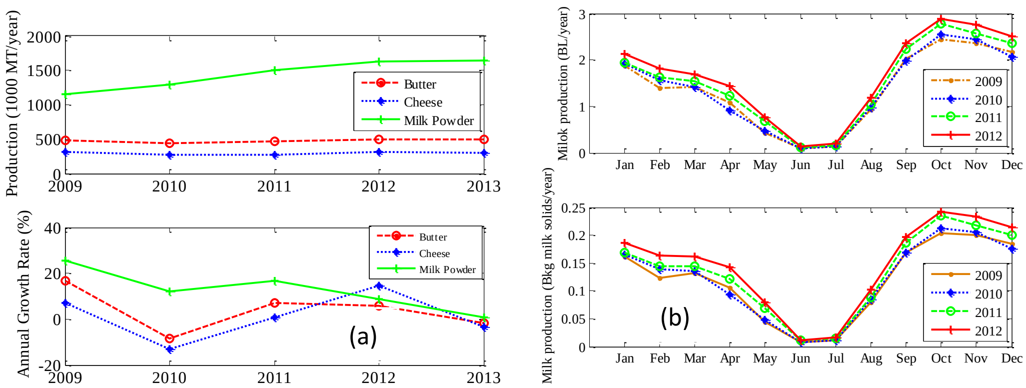

Figure 1. Growth of dairy **(a)** and milk productions **(b)** in NZ in recent years

Milk is converted to a milk powder to reduce the bulk for storage, transport and enhance storage like by removing water or water activity. New Zealand is one of the world's largest producers of dairy products especially milk powder. According to the United States Department of Agriculture (USDA) 2013 report on world markets and trade, New Zealand is one of the largest producers of milk powder, producing around 1665 k MT/yr. China (1665 k MT/yr.) and EU – 27 (1665 k MT/yr.) are other large producers of milk powder as shown in Figure 2 (USDA 2013).

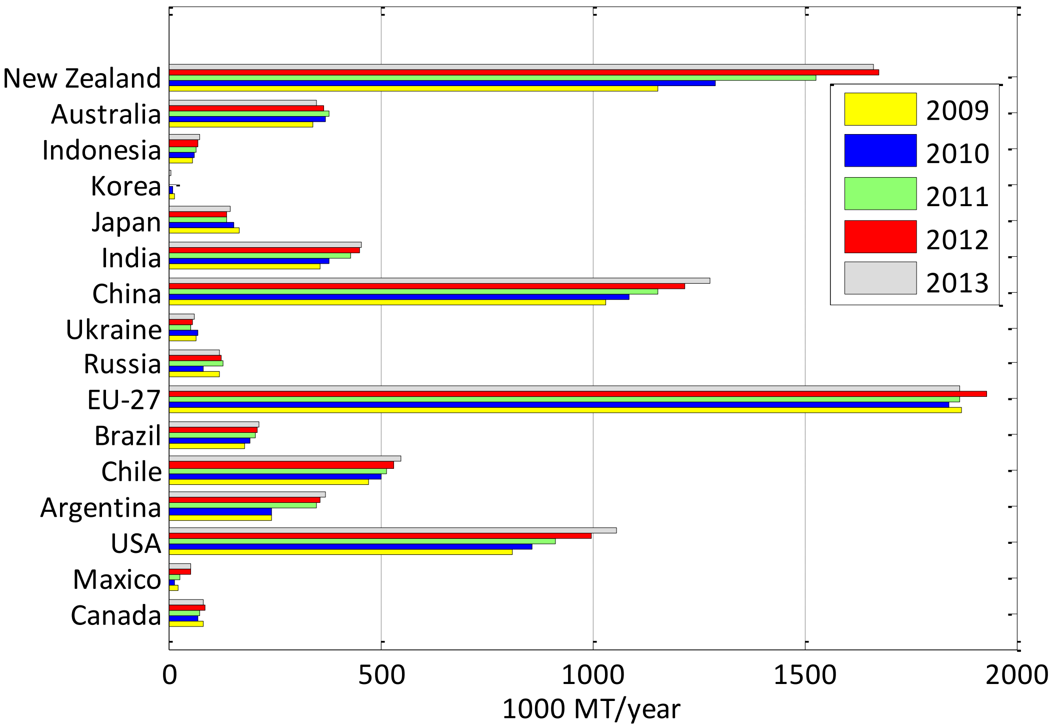

Figure 2. Worldwide milk powder production in recent years

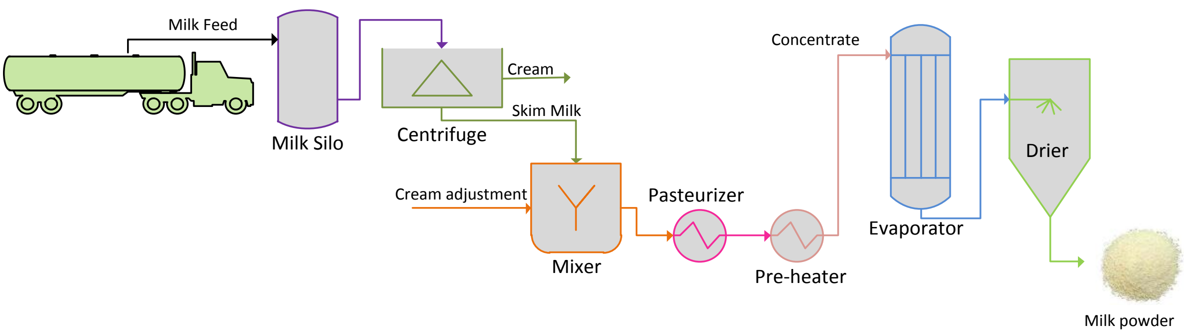

Figure 3. Milk powder manufacturing process schematic

Milk powder production plant involves several units as shown in Figure 3. In milk powder production plant, milk from dairy farms is stored in large milk silos at ≈ 4 °C until used for processing. The milk then goes to a centrifuge to separate the cream (≈ 88 % fat on dry basis) and skim milk (≈ 1.5 % fat on dry basis) fractions. The skim milk stream is then sent to mixers and then to the pasteurizer after adjusting its fat content. During pasteurization, skim milk is heated to 72 °C, and cream is heated to 80 °C for 15 sec to kill the major strains of pathogenic microorganisms. The milk is then preheated to a temperature of between 75 – 125 °C before entering into the evaporator train. In evaporator, milk is concentrated from 12 – 13 % w/w to 48 – 52 % w/w total solids under vacuum at temperatures between 40 – 70 °C. The concentrated milk from evaporator leaves at a temperature between 40 – 58 °C with ≈ 60 % of water removed from milk. The spray drier then atomizes the milk concentrate arriving inside its large chamber. Hot air at a temperature of 180 – 245 °C comes in contact with this atomized milk in a co-current flow pattern producing fine milk powder (Bylund 2003; Goff 2013).

Evaporator in milk powder plant is used to concentrate milk before spray drying to reduce drier load, increase drier feed viscosity and to impose several heat treatments of the milk. In this work, model of a falling film evaporator using a commercial simulator was built and simulated.

Materials and Methods

Milk powder production plant was modelled using the commercial process simulator VMGSim developed by Virtual Materials Group Inc. (VMG) (Virtual Materials Group Inc. 2012). There were other commonly used rigorous commercial process simulators (e.g. Aspen Plus and HYSYS) but VMGSim was selected for the following reasons: 1) user friendly interface, 2) most up to date thermodynamic data, and 3) its ability to incorporate customized calculations using external computer program routines. Recently, VMGSim has also been used to troubleshoot or optimize existing processes, design new processes, and for modelling and control purposes, e.g. (Saber and Shaw 2008; Díaz et al. 2011; Lee et al. 2011; Motahhari et al. 2012; Munir et al. 2012; Munir et al. 2012).

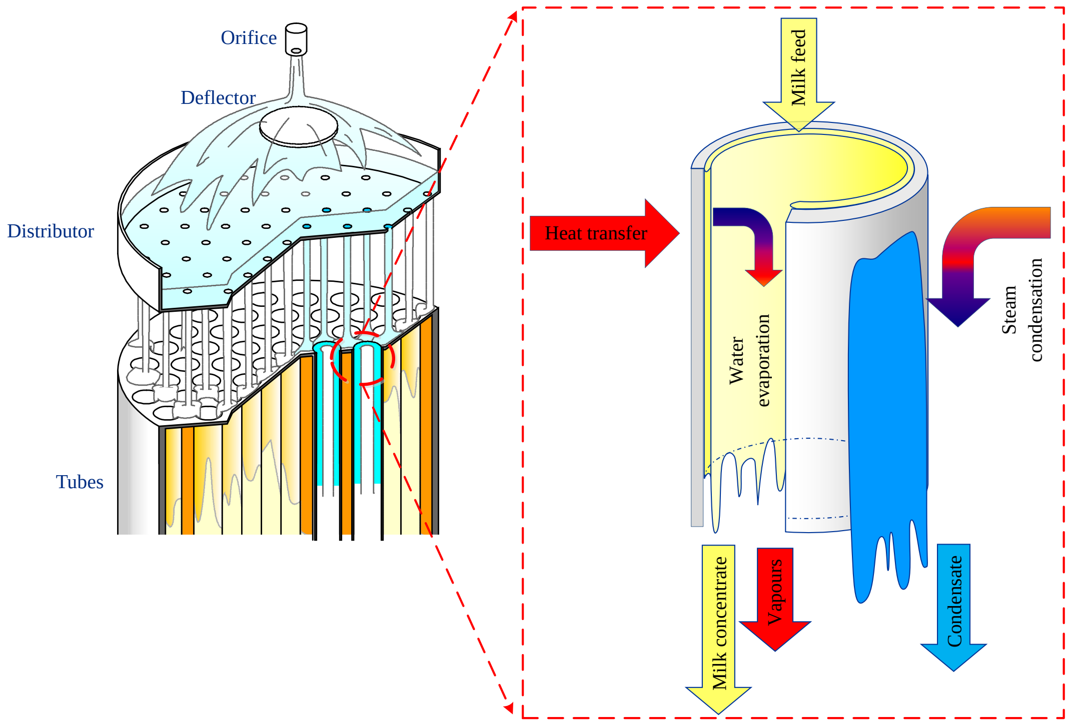

Figure 4. Basic principle of falling film evaporation

The model of falling film evaporator is based on heat transfer through the calandria tube wall. Film-wise condensation on the outer side of the tube (i.e. shell side), convective heat transfer through condensate film, conduction through the tube wall, convective heat transfer through the product (i.e. milk) film and product surface evaporation main heat transfers. Basic principle of falling film evaporation is shown in Figure 4.

Before developing model and simulation of milk evaporator, the “pseudo” milk mixture (with hypothetical components) was developed due to the absence of dairy product components (e.g. milk) in the component libraries of commercial process simulators (e.g. Aspen Plus, HYSYS and VMGSim). The reader is referred to a research article recently published for further details on the “pseudo” milk mixture, and dairy plant modelling in VMGSim (Zhang et al. 2014).

Shell and tube heat exchanger was used to model each effect of the evaporation process with low pressure steam in shell and milk stream in tube side. Both shell and tube sides have two phase systems with varying heat transfer coefficients. However, a constant heat transfer coefficient is a reasonable assumption in this case. Broome (2005) and Ang (2011) explained the detailed calculation procedure for milk evaporator heat transfer coefficient.

Results and Discussion

A steady state model of a multi-effect falling film evaporator is shown in Figure 5. Multi-effect evaporators are energy efficient and are used to minimise effect of increasing energy cost. Multiple shell and tube heat exchangers connected with each other were used for this model.

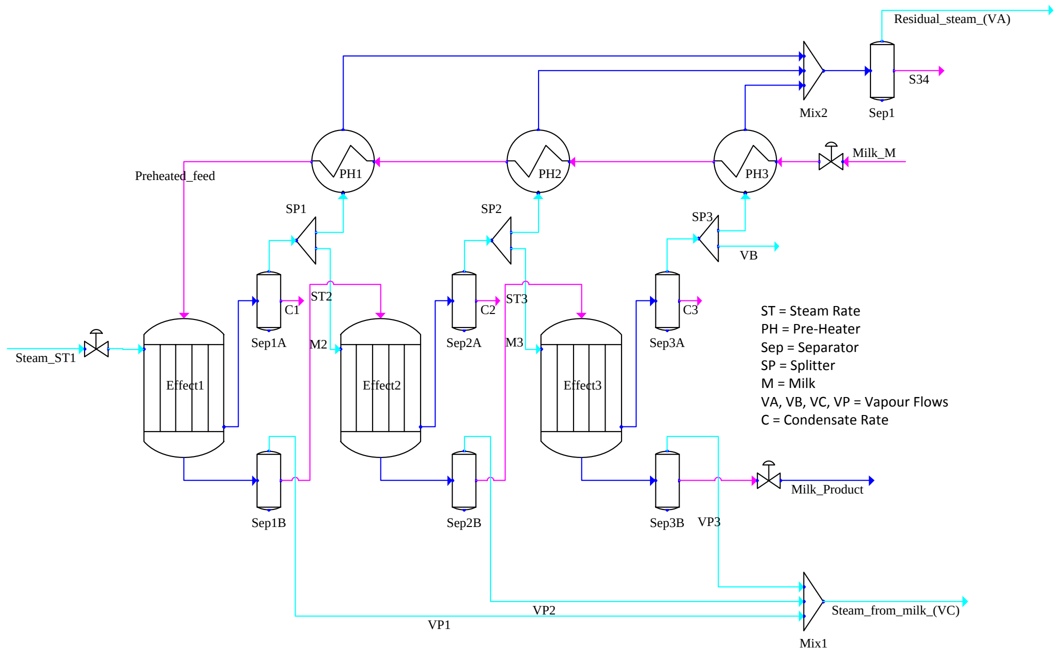

Figure 5. Multi-effect falling film evaporator steady state model

The simulation rresults for the multi-effect evaporator model are shown in Table 1. Table 1 shows a decrease in water content and an increase in viscosity of the milk concentrate (product) stream, with respect to the three effects in order. Total solids and viscosity of the product stream are important to achieve desired properties of milk powder in the dryer (unit operation after evaporator). The results from Table 1 made good sense of multi-effect evaporator mechanisms, and also showed close match with practical and literature and practical data as percent difference between simulation and literature data is 0.1 – 9.4% . The simulated milk densities, thermal conductivity, heat capacity and viscosity results were compared to real milk literature data. For example, (McCarthy and Singh 2009) and (Fernández-Martín 1972) for milk densities, (Hall and Hedrick 1966) for milk thermal conductivity, (Hu et al. 2009) for milk heat capacity and (Souza 2011) for milk viscosity respectively.

Evaporation rates and heat transfer coefficients are higher in 1st two evaporator effects. With increase in evaporator effect number, evaporation rate, heat transfer coefficients and change in final product water content decreases.

It is rare to find a reported study of evaporator lumped model in dairy processing industry due to non-availability of dairy components in the component library of recent simulators, complex physical, chemical and biological structure of the dairy products.

Table 1. The simulation results of a three stage multi-effect evaporator

	Properties	Value	% Difference	Component	Mass Fraction
Effect 1	*ρ*	1050	0.96	Water	**0.70**
	Cp	99.85	0.20	Fat	0.092
	k	0.53	0.15	Proteins	0.078
	µ	*0.54*	*9.4*	Lactose	0.110
	UA	5 x E5		Minerals	0.018
Effect 2	*ρ*	1077	0.99	Water	**0.601**
	Cp	112	0.33	Fat	0.123
	k	0.49	0.19	Proteins	0.104
	µ	*0.64*	*7.3*	Lactose	0.147
	UA	1 x E5		Minerals	0.025
Effect 3	*ρ*	1104	1.08	Water	**0.502**
	Cp	128.5	0.37	Fat	0.153
	k	0.45	0.22	Proteins	0.130
	µ	*0.80*	*5.5*	Lactose	0.184
	UA	6 x E4		Minerals	0.031

where,
ρ = Density *(kg/m³)*,*Cp* = Heat capacity *(kJ/kmol - K)*, *k* = Thermal conductivity *(W/m - K)*, *µ* = Viscosity *(cp)*, *UA* = Overall heat transfer coefficient *(W/K)*

A dynamic model of multi-effect falling film evaporator was also developed with some basic control loops using the commercial process simulator VMGSim as shown in Figure 6. Dynamic model was developed for describing the falling film milk evaporation process, to determine the dynamic effects of potential disturbances, to tune or to evaluate alternate control structures, and to optimize the operation of evaporator.

The dynamic model was validated with real and literature data after its development. A snapshot of dynamic model control performance is shown in Figure 7. Figure 7 shows composition control set point tracking and dynamic historian a plot, showing that mass fraction of final product is kept nearly constant by manipulating heater heat duty to the evaporator. A (± 4 %) set point change (i.e. 48 – 52 % Total solids) on the composition controller (CC) was performed. Other installed inventory control loops which are less important were also working properly but not shown here.

In this work, evaporator dynamic model was tested with simple and basic control structure. Though, it requires further testing with complex disturbances and design of advanced control structures. Gain scheduling can also be used to improve controller performance.

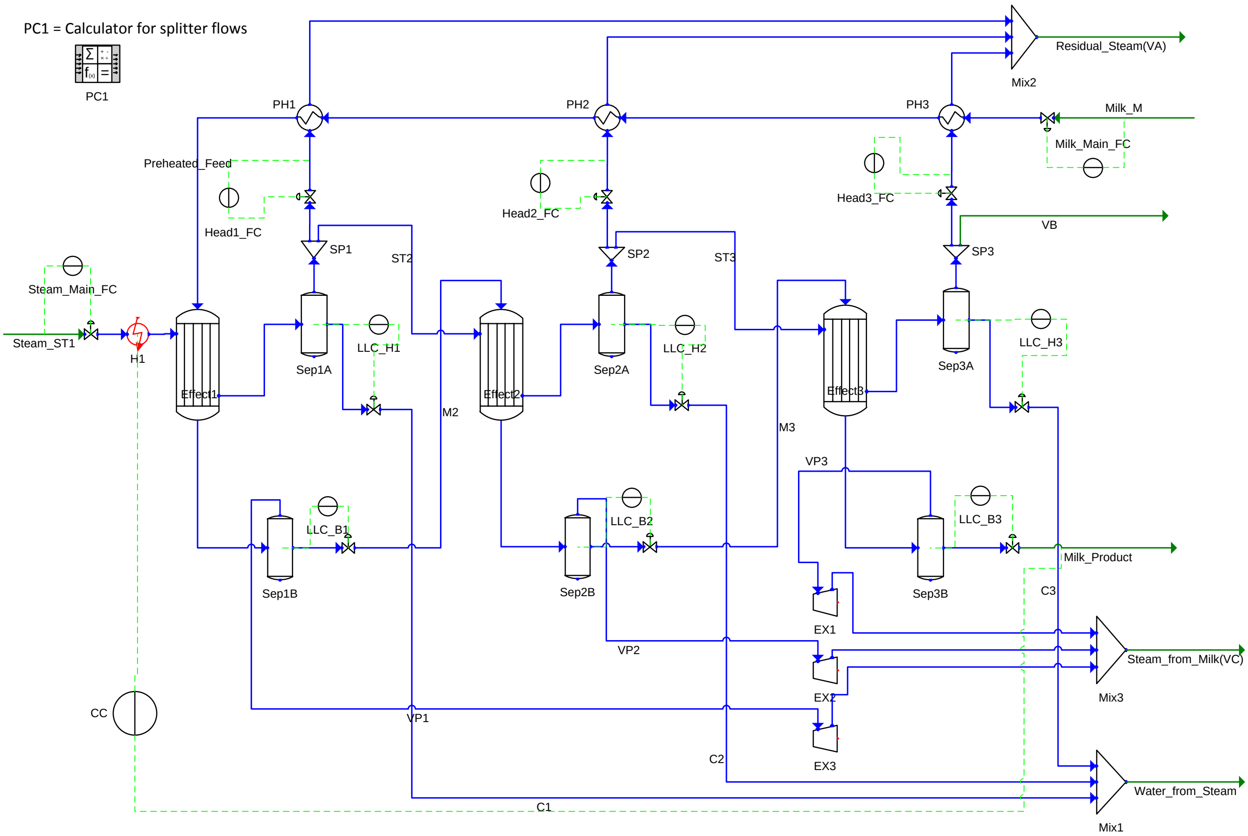

Figure 6. Multi-effect falling film evaporator dynamic state model

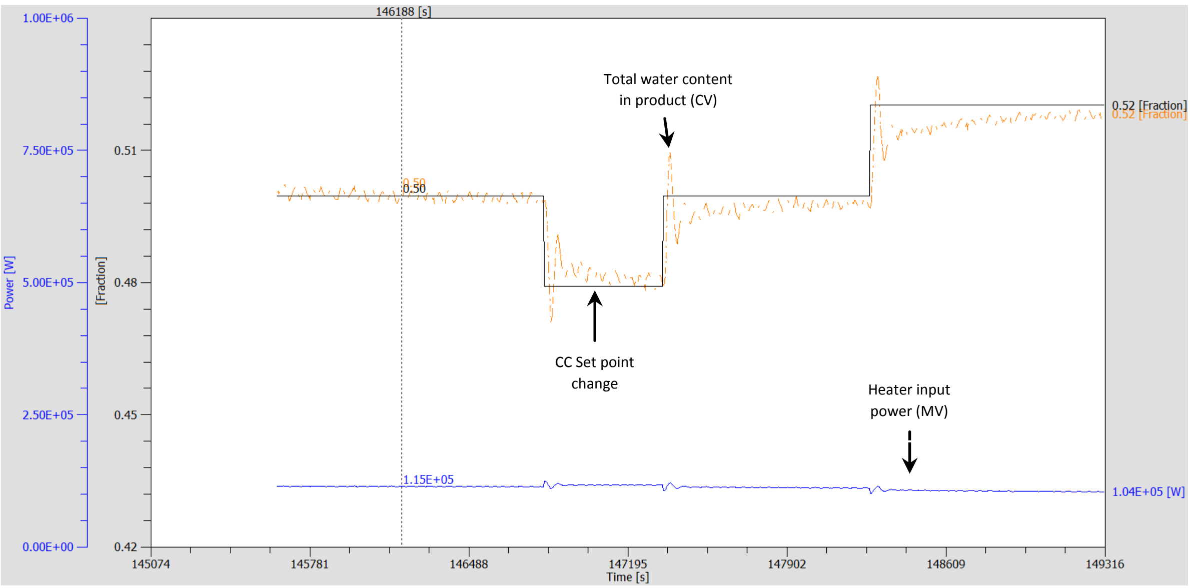

Figure 7. Snapshot of dynamic model control performance

Conclusions

In this work, model of a falling film evaporator using a commercial simulator was built and simulated. The validation of the falling film evaporator model against both, literature and industry data showed that commercial process simulator (i.e. VMGSim) has a capability to simulate the dairy processes.

This model can help practicing process engineers to identify potential disturbance spots and sensivity effect of each process variable due to input variables. It can also help to understand potential process improvements in terms of energy efficiency and savings.

Acknowledgment

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Biography

Taj Munir (Presenter)

Dr Taj Munir received his PhD degree in the Department of Chemical and Materials Engineering at The University of Auckland, New Zealand in 2012. His PhD research involved designing controllable and eco-efficient plantwide control structures. Since 2012, Taj has been working with both Department of Chemical and Materials Engineering at The University of Auckland and Industrial Information & Control Centre (I2C2). He also contributes to a range of other projects including process plant simulation and process analytical technologies (PAT) for quality improvement.

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