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Modeling the Effect of Temperature on Brix Concentration of Tomato Juice during Vacuum Concentration

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Abstract

Concentrated tomato is produced typically from tomatoes by the conventional method of concentration. Recently, vacuum-concentration processes have been developed to concentrate and reduce the variation caused by high temperature. The aim of this study is to simulate water evaporation and change of tomato juice concentration during vacuum concentration. Mathematical and simulation models for vacuum condensate system are proposed and implemented. Matlab's ode45 function is used to solve differential equations and simulate systems. The effect of the concentration and condensate temperature on the Brix concentration of the solution was investigated based on the model. Experiments were carried out with 10kg of tomato juice, the initial Brix concentration was 4, with the concentration temperatures of 60 °C and 65 °C, resulting in the correlation coefficient R^2 reaching 0.9624 and 0.9837, respectively. This result shows a high compatibility between simulation and experiments. The simulations accurately represent the kinetics of the concentration process and the change in temperature and Brix of tomato juice products in the concentration chamber.

Keywords: Concentration, vacuum, modelling, tomato.

1. Introduction

Tomato (Solanum *lycopersicum*), a widely cultivated fruit rich in vitamins, ranks among the top five vegetables globally with a contribution of 67 million tons to the 2019 world vegetable production [1, 2]. They are widely consumed around the world because of its highly versatile ingredients that can be used to add flavor, color, and texture to many different food products. Furthermore, tomatoes have been reported to possess desirable nutritional properties and are considered an essential source of nutrients in many diets. Tomatoes are especially rich in carotenoids (lycopene, β-carotene), vitamin C and polyphenolic compounds [3]. Many research suggest a link between consumption of tomato products and improved immune response, as well as reduced risk of cardiovascular disease and some cancers [4].

A wide variety of processed tomato-based products such as tomato juice, ketchup, and paste have been developed and are available worldwide. Due to the fact that only a small portion of tomatoes are consumed fresh as a seasonal fruit, tomato paste serves as the primary ingredient in 75% of all products derived from tomatoes. It is simply produced by heat treatment at home or industrial production [5]. The transformation of tomato juice to paste has long been a significant issue due to the adverse changes in aroma and flavor that occur during thermal treatment, affecting the quality of the resulting paste. In this respect, vacuum concentration, as a method of reducing processing temperatures, increases the quality and safety of foods by overcoming its heat-sensitive properties.

Heating treatment is the most common processing method widely used to produce food products. In this respect, the final product experiences a temperature gradient during processing. From the point of view of nutritional value, processors and consumers attach great importance to maintain high levels of vitamin content in food [6]. Conventional heat treatment methods require heat energy to be infused from outside into the food by means of heat transfer: conduction, convection, or thermal radiation. Local heating at the heat exchange surface can lead to product quality alteration. Heat treatment technology aimed at avoiding local heating is being developed and is of interest not only in the food industry but also in other sciences.

In recent years, several studies have been carried out to develop alternative concentration methods for traditional ones such as: vacuum concentration; ultrasound-assisted concentration; microwave-assisted concentration or, most recently, ohmic evaporative concentration. These new methods reduce the disadvantages of traditional concentration methods such as waste of steam and processing time [7]. The condensation process carried out at low temperature by applying vacuum has many advantages of which the most prominent is the minimizing product quality loss.

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Vacuum application is a common technique, accompanied by many food processes (evaporation, distillation, crystallization, cooling, drying, concentration) to prevent oxidation reactions (e.g., such as lipid oxidation, vitamin loss, browning due to oxidation or loss of pigment, etc.), or prevent product from overheating and avoid excessive heat to the products that are particularly susceptible to heat damage. Since the boiling point of fluids decreases with decreasing the atmospheric pressure, in the vacuum concentration, by creating a vacuum, the surface pressure of the fluid is reduced, and the fluid evaporates at a lower temperature. As a result, it helps to prevent thermal degradation of the product while reducing the time and energy consumed in the concentration process [8]. Vacuum condition also prevents the oxidation reactions. Therefore, vacuum concentration can have different advantages. Concentration models in previous studies were often developed for atmospheric pressure conditions or in thermo-concentration systems [9, 10]. However, information on the simulation of vacuum concentration is limited.

The purpose of the study is to build a model and analyze the effect of the concentration pressure and cooling water temperature on the change of degrees Brix concentration, evaporation rate and concentration time during vacuum concentration of tomato juice. The differential equations were adjusted for the vacuum condensation phase by applying boundary conditions and the ode45 differential equation solver in MATLAB software (R2020b, MathWorks, USA). By simulating the developed equations and conducting validation experiments, this study aims to evaluate the results of the predicted model with the experimental results, and at the same time correcting the results of the model to match the vacuum concentration process.

2. Materials and Methods

2.1. Materials

2.1.1. Tomato sample

Fresh tomato samples were purchased from supermarkets in Hanoi. The selected tomatoes were mature, uniform in color (red ripe fruit >90% of covered area) and not crushed or damaged by pests.

Fig. 1. Fresh tomato sample after washing

2.1.2. Vacuum Concentrator

The vacuum concentration process is carried out in a vacuum concentrator system (Didacta, Italy) at the Center for Training and Food Product Development - School of Biotechnology and Food Technology - Hanoi University of Science and Technology. The main components in the vacuum concentrator system are vacuum chamber, water ring vacuum pump, stirring motor, secondary vapor condenser, temperature, and pressure gauges. The paddle-type stirrer, 15 ± 1 rpm, ensures uniform mixing of the solution during concentration and avoids local heating. The vacuum chamber has a cylindrical shape, 50 cm diameter, a spherical cap bottom and a maximum working volume of 40 liters. The heat to raise the temperature of the juice is provided by saturated steam through the second shell at the bottom of the concentrator chamber, the heat exchanger surface is spherical cap.

Fig. 2. Vacuum concentrator system (Didacta, Italy)

2.1.3. Other devices

The hammer mill, scrubber, and heating device are equipment in the research and development line for fruit and vegetable products at the Center for Training and Food Product Development. These devices, manufactured by Didacta (Italy), ensure good operation. The degrees brix of the tomato juice was measured by hand-held refractometers.

2.2. Research Methods

2.2.1. Prepare tomato juice

100 kg of fresh tomatoes were washed before being put into a hammer mill with a rotation speed of 1000 rpm. Tomatoes after crushing are heated by a

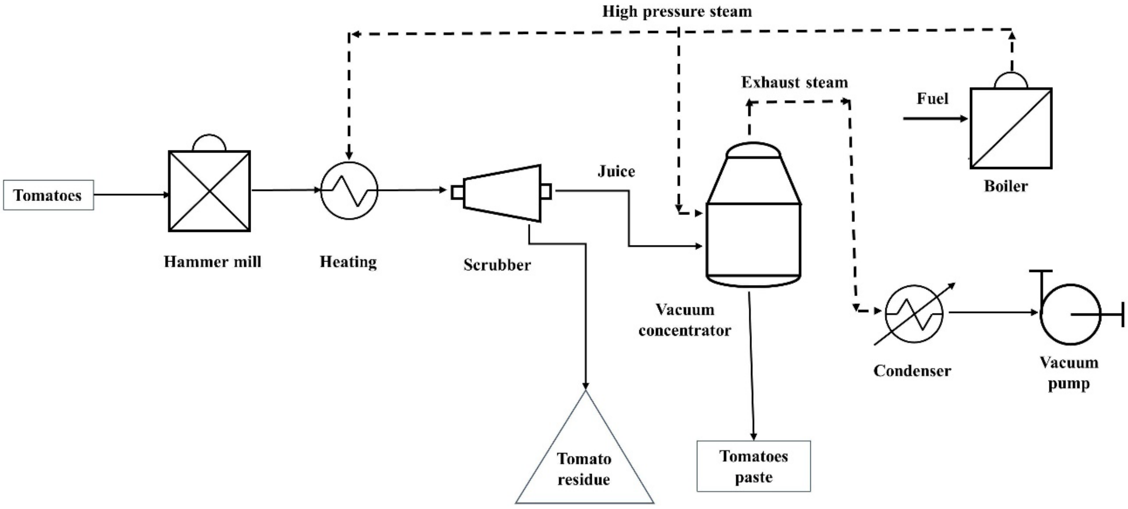

Fig. 3. Tomato Concentration Process Flowchar

screw heater to raise to a temperature of 60 ºC for about 30 seconds to increase the ability to separate the skin and fruit pulp. The heated tomato mixture was then transferred to a scrubber equipped with a 1 mm mesh to separate the skins and seeds and obtain tomato juice.

2.2.2. Vacuum concentration of tomato juice

The process of tomato concentration was experimented with 10 kg of juice per batch at two different boiling temperatures of 60 ºC and 65 ºC. The boiling point of tomato solution during concentration was adjusted by maintaining the vacuum pressure and the amount of steam used to heat the solution. The secondary vapor was condensed through a beam-tube heat exchanger with water. The amount of condensate from the secondary steam is accumulated in a condenser with gauge marks for volume and flow determination. After each concentration period of 180 seconds, the concentrate was sampled for degrees Brix concentration and condensate determination. The concentration was ended after 30 minutes or when the degrees Brix (ºBx) reached 10. The experiment was repeated twice at each temperature.

The flowchart depicting the tomato concentration process in the study is shown in Fig. 3

2.2.3. Process modeling

To model vacuum concentration, we assume the following factors:

1) The entire amount of fluid in the concentration process is heated and controlled stably at the survey temperature.
2) The rate of water evaporation is adjusted steadily so that there is no phenomenon of steam rising with the dissolved substance in the solution.

Assume that the initial solution has a mass M [kg] and has a degrees Brix concentration of Bx_0. To calculate and simulate the concentration process, it is necessary to establish an equation describing the rate of water evaporation of tomato juice during the process. The rate of evaporation depends on many factors and is a relatively complex function [11]. In this study, the equation proposed by Jobson [12] was used to describe the evaporation rate. This equation also can be used to model the concentration of tomato juice. The juice is viewed as a mixture composed of water and dissolved solids, neither of which have a chemical reactivity. The correctness of equation (1) has been verified by Bemporad [13] and H. Ambarita [11] during the experimental process of evaporating seawater.

$$\frac{dm_v}{dt} = A_{sur}.\alpha_m.[f(Bx).\frac{P(T_S)}{(T_S+273)^{0,5}} - \frac{P(T_f)}{(T_f+273)^{0,5}}] \quad (1)$$

where:

- m_v [kg] is the amount of water evaporating in the process;
- A_{sur} $[m^2]$ is the evaporation surface area;
- α_m $[\text{kg}.m^{-2}.Pa^{-1}.s^{-1}.K^{-0,5}]$ is an experimental coefficient;
- T_S [C] is the boiling temperature of tomato juice;
- T_f [C] is the temperature of the water entering the heat exchanger to condense the secondary vapor.

Experimental coefficient α_m is proposed by Al-Kharabsheh [14] when sudying the evaporation of seawater with the value: $10^{-7} \le \alpha_m \le 10^{-5}$. Al-Kharabsheh's experimental equipment is similar to that used for tomato juice concentrate equipment, in terms of device structure: the surface evaporation area is about 0.2 m^2, and the working pressure is about 0.3 atm. The hypothesis includes the evaporation of water without solute loss. Therefore, the experimental coefficient interval α_m mentioned above is included as a boundary limit for the simulation. Through the survey, the suitable α_m value for tomato juice in this experiment is:

$$\alpha_m = 1{,}7.10^{-6}\ [\mathrm{kg}.m^{-2}.Pa^{-1}.s^{-1}.K^{-0{,}5}].$$

The vapor pressure P(T) [Pa] is a function of the temperature given by:

$$P(T) = 100.e^{63{,}042-\frac{7139{,}6}{T+273}-6{,}2558.ln(T+273)} \quad (2)$$

The correction parameter $f(Bx)$ can be calculated by the formula (Keren *et al.*, 1993 [15]):

$$f(Bx) = 1 - 0.0054.Bx \quad (3)$$

Degrees Brix is a unit of measurement for evaluating any dissolved solids in plant juices (fruits and vegetables). These solids include amino acids, proteins, minerals, vitamins and sugars. In this study, the assumption is that the evaporation rate is adjusted steadily so that there is no evaporation that washes away the dissolved substance in the concentrated juice. At one point, the equilibrium equation of °Bx is set up as follows:

$$Bx = \frac{M.Bx_0}{M - m_v} \quad (4)$$

Derivate equation (4) with respect to time give us:

$$\frac{d(Bx)}{dt} = \frac{d}{dt}\left(\frac{M.Bx_0}{M - m_v}\right) = \frac{M.Bx_0}{(M - m_v)^2}.\frac{dm_v}{dt} \quad (5)$$

2.2.4. Simulation of the process

To simulate the condensation process, a system consisting of differential equations (1)-(5) needs to be solved. In which, the quantities m_v và Bx were functions over time. Simulations were performed by MATLAB software and using Matlab's standard solver for the equations and systems of ordinary differential equations (ODEs) as the function *ode45*. The basis of the *ode45* function is an implementation of the Runge-Kutta formula with a variable time step.

$$\frac{dx}{dt} = f(t,x), x(t_0) = x_0 \quad (6)$$

where:

- t is time (independent variable);
- x is the vector of the dependent variables;
- $f(t,x)$ is a function of t and x;
- x_0 are the values of x at the beginning t_0.

2.2.5. Statistical rating

The compatibility of the simulation model is assessed by: Root Mean Square of Error (RMSE), Mean Square of Error (MSE) and the R-Square value (R^2).

$$RMSE = \sqrt{\frac{\sum_i^n (f_i - y_i)^2}{n}} \quad (7)$$

$$MSE = \frac{\sum_i^n (f_i - y_i)^2}{n} \quad (8)$$

$$R^2 = 1 - \frac{\sum (f_i - y_i)^2}{\sum (f_i - \overline{y})^2} \quad (9)$$

where:

- f_i is the estimated value according to the model
- y_i is the actual measured value.
- $\overline{y}$ is the average of the actual measured value

2.3. Time and Place of Research

This research was carried out from November 2021 to April 2022 at the Center for Training and Food Product Development, School of Biotechnology and Food Technology, Hanoi University of Science and Technology.

3. Results and Discussion

3.1. Tomato Juice Vacuum Concentration

The tomato juice vacuum concentration experiment was carried out using 10 kg of raw material juice with an initial degrees Brix of 4°Bx. The parameters of the concentration process at different temperatures were shown in Table 1.

At a concentration temperature of 60 °C, the experiment was stopped after 11 sampling cycles, which corresponded to 33 minutes. However, at a temperature of 65 °C, the experiment was stopped after 10 sampling cycles, corresponding to 30 minutes. At the end of the experiment, the degrees Brix of the product sample reached an average of 10°Bx. The concentration process was stopped because the remaining amount of juice was relatively smaller than 5 liters compared to the working volume of the concentrator. The amount of condensed water at the temperature of 65 °C was higher than the amount of condensed water at 60 °C at the corresponding time. This shows that the higher the temperatures, the greater the evaporation rate.

The degrees Brix concentration of the tomato juice increased over time as it was concentrated. The increasing of degrees Brix was directly relating to the density of the solution. The Brix concentration also depended on the amount of water evaporated during experiment.

Table 1. Vacuum concentration process of tomato juice at 60 °C and 65 °C

Time (s)	**Degrees Brix**	**Amount of condensed water (kg)**	**Time (s)**	**Degrees Brix**	**Amount of condensed water (kg)**
60 °C			***65 °C***		
0	4.0	0.0	0	4.0	0.0
180	4.1	0.20	180	4.2	0.22
360	4.1	0.65	360	4.2	0.48
540	4.3	1.11	540	4.6	0.93
720	4.4	1.77	720	4.8	1.61
900	4.6	2.44	900	5.8	2.37
1080	5.0	3.06	1080	6.0	3.16
1260	5.8	3.73	1260	7.2	3.94
1440	6.4	4.26	1440	8.0	4.69
1620	7.0	4.93	1620	9.2	5.41
1800	8.4	5.60	1800	9.9	6.11
1980	10.2	6.48			

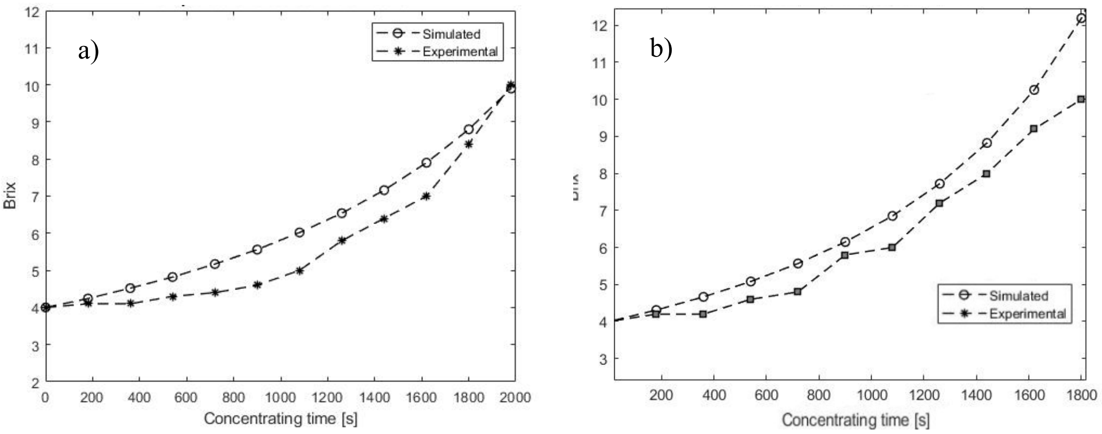

Fig. 4. Compare the model with the experiment at concentration temperatures (a) 60 °C and (b) 65 °C

3.2. Comparison of Model Predicted and Experimental Results

The predicted results of the model and the experimental results when tomato juice was concentrated at 60 °C and 65 °C with an initial degrees Brix of 4 °Bx are shown in Table 2. The comparision between the estimated Brix values from the model and the actual results is shown in Fig. 4.

The results of the estimated values and the measured experimentally degrees Brix values can be used to calculate the Correlation Coefficients (R^2), the Mean Squared Error (MSE) and the Square Root of Mean Square (RMSE), as shown in Table 2.

The evaluation indexes of the model were compared and the relatively high R^2 shows that the constructed model is consistent with the actual results. At a temperature of 60 °C, the R^2 reached 0.9624, which is less than the corresponding value of 0.9837 at 65 °C. However, Mean Squared Error (MSE) value was smaller at 60 °C than 65 °C.

Table 2. Statistic index table for model evaluation

Models	R^2	MSE	RMSE
At the boiling temperature of 60 ºC	0.9624	0.4272	0.6536
At the boiling temperature of 65 ºC	0.9837	0.7967	0.8626

*3.3. **Simulation of Water Vaporation from Tomato Juice at Different Temperature.***

Performing a simulation of the vacuum concentration process on the device with 10 liters of tomato juice, the initial degrees Brix is 4 ºBx, the evaporation surface area was estimated by the cross-sectional area of the vacuum tank $A_{sur} = 0.196\ m^2$. Simulated concentration temperatures at values 50, 55, 60, 65 and 70 °C.

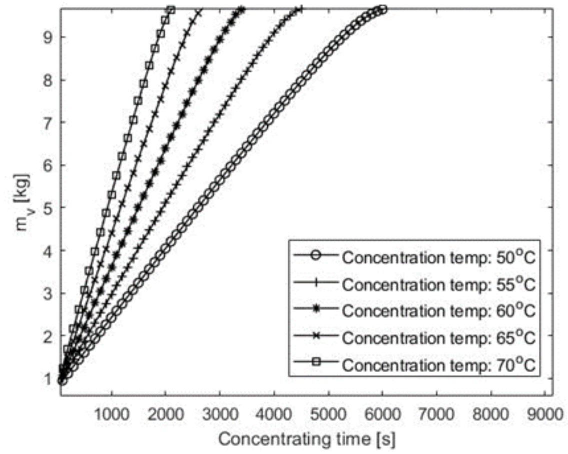

Fig. 5. Graph simulating the amount of evaporated water at different concentration temperatures

The simulation results shown on Fig. 5 indicate differences in the rate of water evaporation at different temperatures. At high temperatures, the rate of evaporation occurs faster. Some studies have shown that the temperature of the concentrate solution tends to increase during boiling, leading to an increase the boiling point called Boiling Point Rise (BPR). This increase in boiling point that causes the vapor to escape faster than at normal boiling points. At a concentrated temperature of 50 °C, the curve for the time it takes for water to vaporizaze almost constant during the concentration process. However, at the end of the process, when the amount of water evaporated exceeds 9 kg, the evaporation rate decreases and the graph takes the form of a line parallel to the horizontal axis in Fig. 5.

3.4. Simulation of Changes in degrees Brix Concentration of Tomato Juice at Different Temperatures.

The simulation of degrees Brix over time and temperature of concentration was conducted using the input parameter as described above.

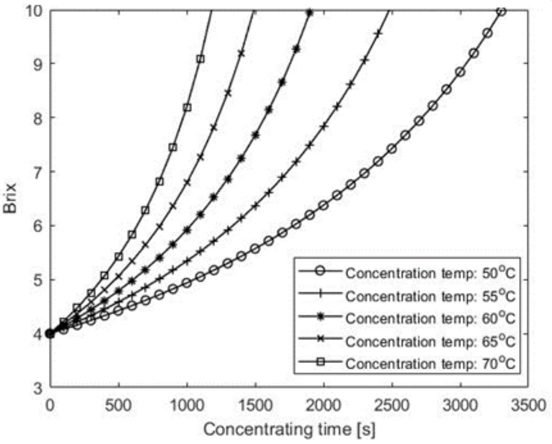

Fig. 6. Graph of degrees Brix changes of tomato juice at different concentration temperatures

As shown in Fig. 6, increasing the boiling temperature of concentrate results in a shorter working time. This relationship can be explained by equation (3), as the boiling point of the concentrate is directly proportional to the rate of water evaporation during vacuum concentration, which in turn shortens the concentration-time required to achieve the maximum degrees Brix. At the same time, The degrees Brix concentration does not increase linearly with concentration time, but rather a curve that roughly resembles a branch of the parabolic graph. At the concentration temperature of 55 °C, the increase in degrees Brix concentration between the concentrate time from 1000 to 3000 seconds is almost linearly.

3.5. Simulation of Changes in degrees Brix Concentration of Tomato Juice at Different Condensed Water Temperatures

Another simulation was done to investigate the effect of the condenser cooling efficiency on the performance of the vacuum concentration system. In this simulation, the boiling temperature of the concentrate was kept fixed at 60 °C and the coolant water temperature before entering the condenser was 20 °C. The cooling efficiency of the condenser was controlled by varying the flow rate of the coolant, resulting in the changes of the heat exchange efficiency between the steam released during concentrate and the cooling water temperature. This efficiency also affected the final temperature of the condensed water after exiting the condenser. The results of the cooling efficiency's effect on the system's performance are shown in Fig. 7.

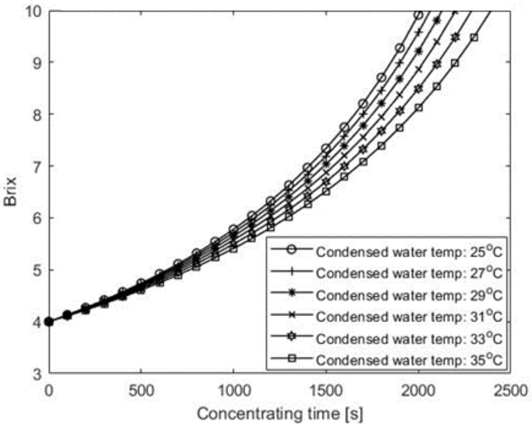

Fig. 7. Graph of the change in the degrees Brix concentration of tomatoes at 60 °C with different levels of condensed water temperature

Fig. 7 showed that the lower temperature of the condensed water, the better the cooling efficiency and the more efficient the condenser was. With condensing time from 4°Bx to 10°Bx at a condensed water temperature of 35 °C is 1807 seconds while at 25 °C, the condenser water temperature was only 1510 seconds. This result shows that the cooling efficiency of the condenser strongly influences the concentration process. Indeed, when large amount of water is released and the condenser fails to respond in time, vapor accumulates, creating a partial pressure that hinders the evaporation of the concentrate.

4. Conclusion

In this study, the evaporation equation in the vacuum concentrator was modeled and the process was simulated using MATLAB's *ode45* solver. The hypotheses were simplified and boundary conditions were used to develop diffirential equations for water evaporation. The built model also investigated the concentration-dependent change in evaporation rate. The results showed that higher vacuum pressure led to a lower boiling point, which kept the nutrient content of the product intact but increased the concentration time. The coolant temperature also affected the condensation process by potentially causing reverse pressurization for the system. The model's predictions showed a good agreement with experimental data.

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