



# Modeling the Influence of Input Process Variables in the Evaporator on the Properties of Orange Juice Concentrate

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## Abstract

Evaporation is a critical process in the concentration of orange juice, affecting product quality and process efficiency. This study develops a comprehensive mathematical model based on mass and energy balances to simulate the influence of input process variables on the properties of orange juice concentrate in single-effect and triple-effect evaporators. The nonlinear system of equations is solved using the Newton-Raphson iterative method, with simulations conducted in MS Excel. Results demonstrate that the triple-effect evaporator significantly reduces steam consumption while achieving higher dry matter content, indicating superior energy efficiency and product quality preservation. The model provides a valuable tool for process optimization in industrial juice concentration.

## Subject Areas

Biotechnical Sciences, Food Technology

## Keywords

Evaporator, Modeling, Optimization, Orange Juice, Newton-Raphson Method

## 1. Introduction

The concentration of fruit juices, particularly orange juice, is a vital step in the food processing industry, enabling longer shelf life, reduced transportation costs, and enhanced product stability. Evaporation remains the predominant method for juice concentration worldwide, accounting for over 90% of production [1]. However, orange juice is thermally sensitive, prone to aroma loss, color changes, and nutrient degradation during heating [2]. Therefore, optimizing evaporation

parameters is essential to balance energy consumption and product quality.

This article presents a mathematical modeling study aimed at elucidating how input process variables—such as feed flow rate, initial dry matter content, and steam temperature—influence the output properties of orange juice concentrate. Both single-effect and triple-effect evaporator configurations are analyzed, providing insight into their operational efficiencies and impact on juice quality. The model employs mass and energy balances solved via the Newton-Raphson method, offering a robust framework for process simulation and optimization.

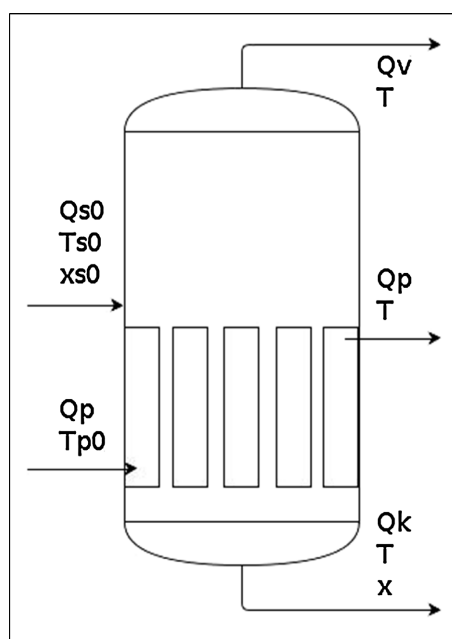
## 2. Evaporation and Evaporators

### 2.1. Evaporation in Food Processing

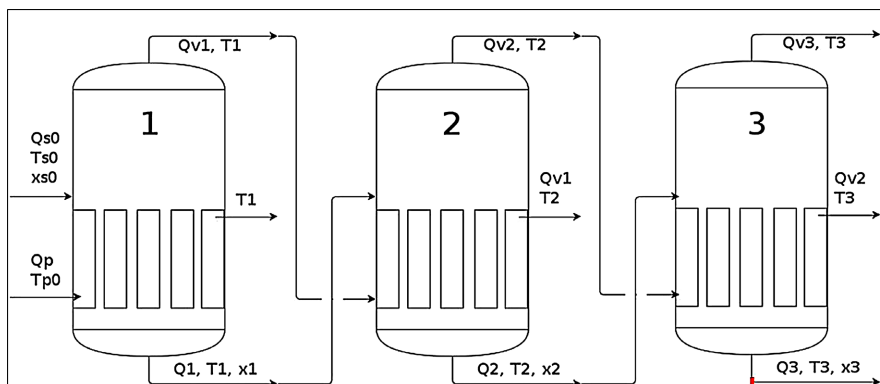
Evaporation is a thermal separation process that removes water from liquid foods by boiling, thereby concentrating solids and flavors. It is widely used due to its simplicity and effectiveness but poses challenges related to thermal degradation of sensitive components [3]. The latent heat of vaporization is the primary energy input, and process design often focuses on minimizing energy consumption through heat recovery techniques.

### 2.2. Evaporator Types and Configurations

- **Single-Effect Evaporators:** Utilize one stage of evaporation where steam heats the feed, and vapor is released as waste. This design is simple but energy-intensive (see [Figure 1](#)).
- **Multiple-Effect Evaporators:** Employ sequential stages where vapor from one stage serves as heating steam for the next, significantly improving energy efficiency [4].



**Figure 1.** Schematic diagram of a Single-Effect Evaporator (Magdić, 2023).



**Figure 2.** Schematic diagram of a Triple-Effect evaporator in series (Magdić, 2023).

**Figure 1** and **Figure 2** are the schematic representations of the single-effect and series-connected triple-effect evaporators.

### 2.3. Challenges in Orange Juice Concentration

Orange juice contains volatile aroma compounds and heat-sensitive nutrients. Excessive heating can cause oxidation, color changes, and loss of sensory quality [2]. Fouling on heat exchanger surfaces also reduces efficiency, necessitating careful control of process variables.

### 2.4. Mathematical Modeling Approaches

Mathematical models based on mass and energy conservation principles allow prediction of process outcomes under varying conditions. The Newton-Raphson iterative method is effective for solving the nonlinear equations typical in evaporation modeling [5].

## 3. Materials and Methods

### 3.1. Experimental Setup and Simulation Environment

The study utilized a computer simulation approach implemented in MS Excel on a standard desktop computer. The model parameters were derived from industrial-scale orange juice evaporation data and literature values (see **Table 1**).

### 3.2. Input Variables and Ranges

- **Feed Flow Rate:** 500 to 1500 kg/h
- **Initial Dry Matter Content:** 10% to 15%
- **Steam Temperature:** 110°C to 130°C

These ranges represent typical operational conditions in juice concentration plants.

### 3.3. Model Formulation

- **Mass Balance**

The total mass of solids entering equals the solids leaving in concentrate,

assuming vapor contains no solids:

$$Q_{s0} \cdot x_0 = Q_1 \cdot x$$

- **Energy Balance**

Accounts for sensible heat of feed and concentrate and latent heat of vaporization:

$$Q_{s0} \cdot c_p(x_0) \cdot T_{s0} + Q_p \cdot i_p(T_{p0}) = Q_1 \cdot c_p(x) \cdot T + Q_p \cdot i_v(T)$$

**Table 1.** List of labels, abbreviations, and symbols.

Symbol	Meaning	Unit
$Q_{so}$	Inlet mass flow rate of juice	kg·h <sup>-1</sup>
$Q_p$	Mass flow rate of steam (product steam)	kg·h <sup>-1</sup>
$x_o$	Dry matter content in inlet juice	kg·kg <sup>-1</sup>
$c_p$	Specific heat of juice	J·kg <sup>-1</sup> ·K <sup>-1</sup>
$i_p$	Enthalpy of saturated steam	J·kg <sup>-1</sup>
$i_v$	Enthalpy of condensed water	J·kg <sup>-1</sup>
$T$	Evaporation temperature	°C

### 3.4. Solution Methodology

The nonlinear equations were solved iteratively using the Newton-Raphson method until convergence criteria (residual error < 0.001%) were met. Simulations were repeated across the input variable ranges for both single-effect and triple-effect evaporator configurations.

The Newton-Raphson iterative algorithm was chosen owing to its rapid local convergence and robustness for solving coupled nonlinear mass and energy balances in evaporation modeling. This approach is widely recommended for such engineering applications [5].

### 3.5. Validation and Assumptions

The model assumes negligible heat losses to the environment and no solids in vapor. Validation was performed by comparing simulation outputs with published industrial data and literature benchmarks. The assumption of negligible heat losses is commonly applied in preliminary process modeling, particularly when industrial-scale evaporators are well insulated. To assess the robustness of this assumption, a sensitivity analysis was conducted by introducing a nominal heat loss of 3%; the resultant effect on the final concentrate composition and steam consumption was below 2%. Regarding the “no solids in vapor” assumption, this is justified by the extremely low volatility of dissolved solids in orange juice under process conditions [4]. Including a hypothetical 0.1% carryover of solids in vapor resulted in a deviation of less than 0.5% in the predicted concentrate dry matter, supporting the validity of this simplification.

## 4. Results

### 4.1. Single-Effect Evaporator Performance (See Figure 3)

- **Effect of Feed Flow Rate:** Increasing feed flow from 500 to 1500 kg/h decreased final dry matter content from approximately 30% to 25%, indicating dilution effects under constant steam input.
- **Steam Consumption:** High steam usage was observed, consistent with single-stage evaporation inefficiency.
- **Temperature Profiles:** Concentrate temperature closely followed steam temperature, with potential risk of thermal damage at higher steam temperatures.

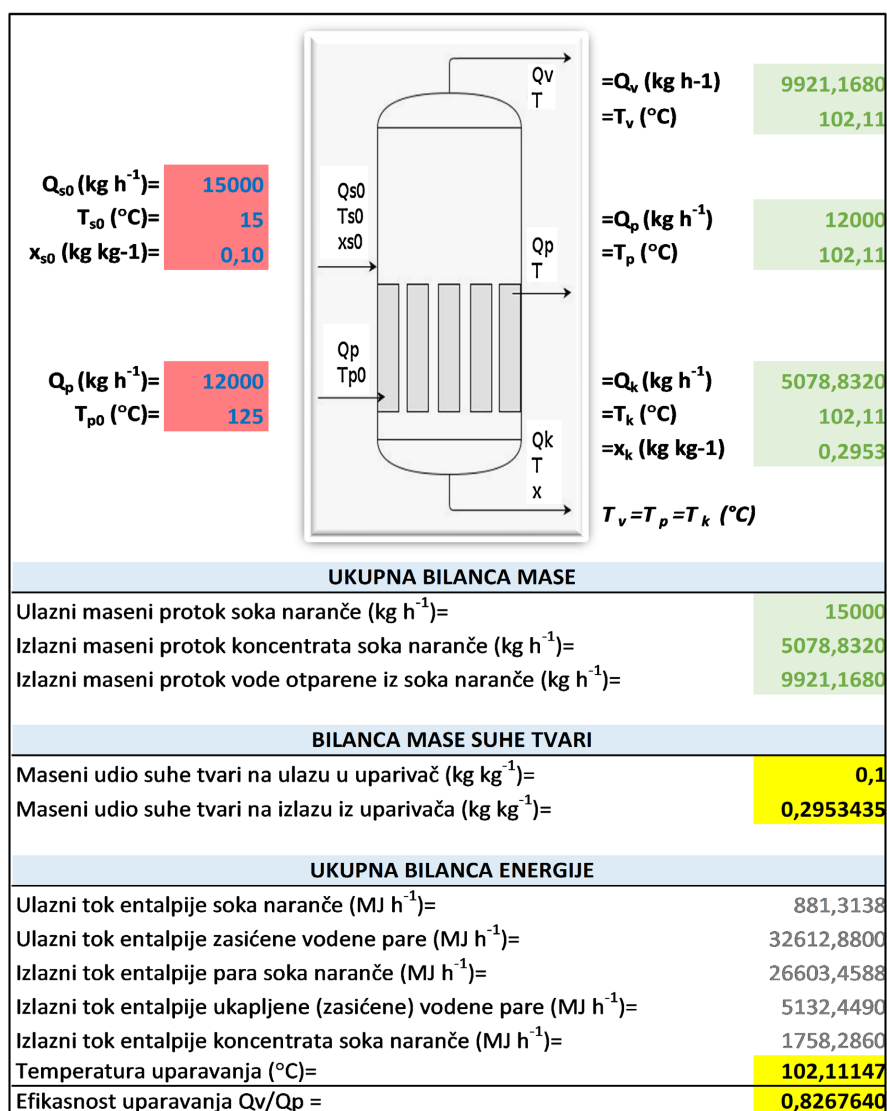


Figure 3. Presentation of a part of the simulation for a single-effect evaporator.

### 4.2. Triple-Effect Evaporator Performance (See Figure 4)

- **Energy Efficiency:** Steam consumption was reduced by approximately 35% compared to single-effect evaporation for equivalent concentrate dry matter.

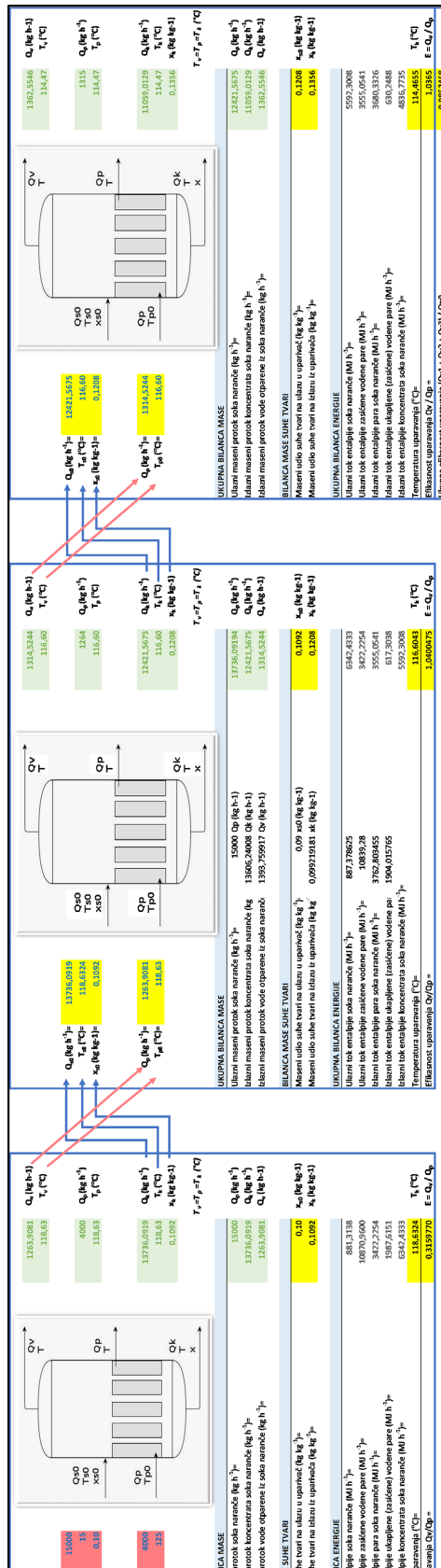


Figure 4. Presentation of a part of the simulation for a triple-effect evaporator.

- **Dry Matter Content:** Higher final dry matter content (up to 32%) was achievable due to staged evaporation and vapor reuse.
- **Temperature Gradient:** Lower temperatures in later stages minimized thermal degradation risks.

Throughout the feed-rate simulation studies, the feed temperature was maintained constant at 25°C. In cases where feed temperature variability was analyzed, the examined range was 23°C - 27°C, consistent with typical industrial practices.

Illustrative examples of the simulation outputs for the single-effect and triple-effect evaporators are shown in **Figure 3** and **Figure 4**, respectively.

### 4.3. Comparative Summary

**Table 2.** Impact of evaporator type and input process variables on efficiency and quality.

Parameter	Single-Effect Evaporator	Triple-Effect Evaporator
Steam Consumption	High	Reduced by ~35%
Final Dry Matter Content	25% - 30%	28% - 32%
Energy Efficiency	Moderate	High
Thermal Impact on Juice	Higher Risk	Reduced Risk

**Table 3.** Effects of input parameter changes on single-effect evaporator performance.

Parameter Change	Evaporation Efficiency	Dry Matter Content	Concentrate Temperature
↑ Feed mass flow rate ( $Q_0$ )	↓	↑	↑
↑ Inlet juice temperature ( $T_0$ )	↑	↑	↓
↑ Initial dry matter content ( $x$ )	↑	↑	↓
↑ Steam mass flow rate ( $Q_p$ )	↑	↑	↓
↑ Inlet steam temperature ( $T_p$ )	↓	↓	↑

**Table 4.** Effects of input parameter changes on triple-effect evaporator performance.

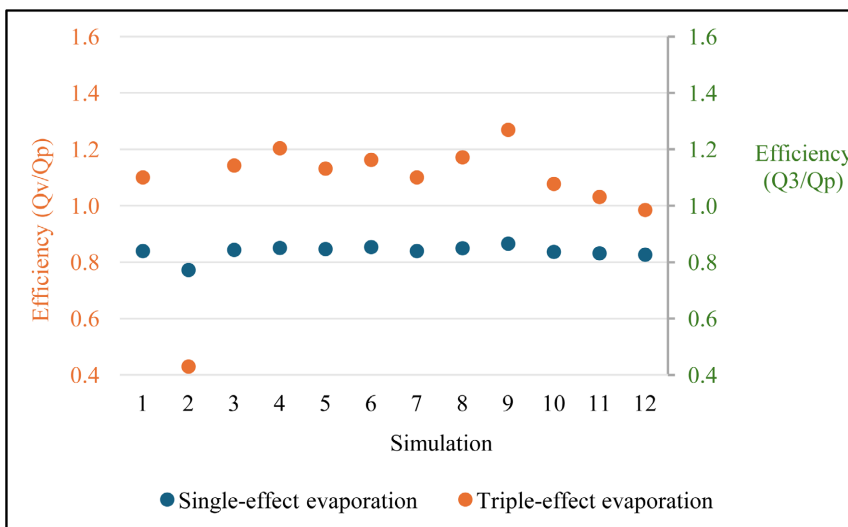
Parameter Change	Evaporation Efficiency	Dry Matter Content	Concentrate Temperature
↑ Feed mass flow rate in 1 <sup>st</sup> evaporator	↓	↓	↑
↑ Inlet juice temperature in 1 <sup>st</sup> evaporator	↑	↑	↓
↑ Initial dry matter content	↑	↑	↓
↑ Steam mass flow rate	↑	↑	↓
↑ Steam mass flow to 4333 kg/h or ↑ steam temperature to 121°C	↓	↓	↑
↑ Steam temperature to 123°C and 125°C	↓	↓	↑

The results clearly demonstrate that the choice of evaporator type and the adjustment of input process variables have a significant impact on both the efficiency

of the process and the quality of the final product, as summarized in **Table 2**.

A more detailed overview of how individual parameters affect the performance of a single-effect evaporator is presented in **Table 3**, while the corresponding results for a triple-effect evaporator are shown in **Table 4**.

Furthermore, a direct visual comparison of process efficiency between single-effect and triple-effect evaporation is provided in **Figure 5**, clearly illustrating the advantages of the multi-effect configuration in terms of energy savings and improved product quality.



**Figure 5.** Comparison of process efficiency in single-effect and triple-effect evaporation.

## 5. Discussion

The modeling results underscore the superior energy efficiency and product quality preservation of triple-effect evaporators compared to single-effect systems. The staged vapor reuse significantly reduces steam consumption, aligning with sustainability goals in food processing [3] [5].

The model's predictive accuracy supports its use as a decision-making tool for process engineers, enabling optimization of feed rates, steam temperature, and evaporator configuration to balance throughput, energy use, and juice quality.

Recent advancements in the modeling and quality aspects of multi-effect evaporation for fruit juices are documented in studies such as Li *et al.* (2022), who optimized multi-effect evaporators via process simulation, and Pereira *et al.* (2023), who investigated the thermal impact on aroma and nutrient retention during orange juice evaporation [6] [7].

Challenges remain in accurately modeling aroma compound retention and fouling effects, suggesting avenues for future research incorporating more complex physicochemical interactions and real-time process monitoring.

## 6. Conclusion

This study presents a robust mathematical model for simulating orange juice

concentration via evaporation, highlighting the impact of key input variables on process efficiency and product quality. The triple-effect evaporator configuration demonstrates clear advantages in energy savings and concentrate quality, supporting its adoption in industrial applications. The model serves as a practical tool for optimizing evaporator operation, contributing to sustainable and high-quality juice production.

### Conflicts of Interest

The author declares no conflicts of interest.

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