Energy Analysis of the Refrigeration System and Its Impact on Process Parameters in Shortening Oil Production

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Abstract

The food industry requires high-quality products, including shortening oil, widely used in bread and cake production. The production process depends heavily on refrigeration system efficiency to maintain temperature stability and ensure product consistency. This study evaluates the performance of refrigeration systems in shortening oil production and examines how suction pressure affects energy consumption and product quality. Simulations using Aspen Plus® and CoolPack were conducted to analyze cooling capacity (Qe), heat rejection capacity (Qc), compressor work (W), and Coefficient of Performance (COP). Increasing suction pressure from 1.2 bar to 1.6 bar improved Qe and reduced W in both software. Aspen Plus® showed Qe increased from 201.01 kJ/kg to 203.98 kJ/kg, while CoolPack showed an increase from 201.50 kJ/kg to 203.36 kJ/kg. Heat rejection (Qc) remained relatively stable, slightly decreasing from 225.81 kJ/kg to 225.57 kJ/kg in Aspen Plus® and from 262.12 kJ/kg to 258.12 kJ/kg in CoolPack. Compressor work dropped from 25.28 to 22.86 kJ/kg in Aspen Plus® and from 60.58 kJ/kg to 54.76 kJ/kg in CoolPack. COP improved significantly, from 7.95 to 8.92 in Aspen Plus® and from 3.33 to 3.71 in CoolPack. Furthermore, product quality improved as shown by an increase in penetration value from 272 mm/s to 314.4 mm/s, indicating a softer texture due to changes in the fat crystallization process. These findings highlight the importance of optimizing suction pressure to enhance refrigeration performance and maintain desired quality in shortening oil production.

Keywords: *Efficiency; Energy analysis; Refrigeration systems; Shortening oil; Simulation*

1. Introduction

The food industry is one sector that continues to grow along with the increasing demand for high-quality food products. Shortening oil is one of the important products in this industry, and it is used in various applications such as bread, cakes, and snacks [1]. Shortening oil is made from vegetable oils through a partial or full hydrogenation process, which converts liquid oils into solid fats with specific physical and chemical properties, such as high oxidative stability and smooth texture [2]. These properties make shortening an essential ingredient for improving the texture, flavor, and shelf life of food products. Shortening oil production heavily relies on refrigeration systems, which play a critical role in maintaining optimal temperatures during key stages such as hydrogenation and cooling [3]. These systems ensure the final quality of the product is preserved, as excessively high temperatures during hydrogenation can lead to the formation of unwanted trans-fats, while inefficient cooling can reduce the textural quality of the final product. Moreover, refrigeration systems are among the main energy-consuming components in production, meaning their efficiency significantly impacts operational costs and the environment [4]-[5].

To illustrate the thermodynamic processes involved, Figure 1 depicts the vapor-compression refrigeration cycle used in shortening oil production. This schematic diagram highlights the four primary components: the compressor, condenser, expansion valve, and evaporator. The figure also identifies the specific points of enthalpy transition (h_1, h_2, h_3, and h_4) and their respective roles in the energy transfer process.

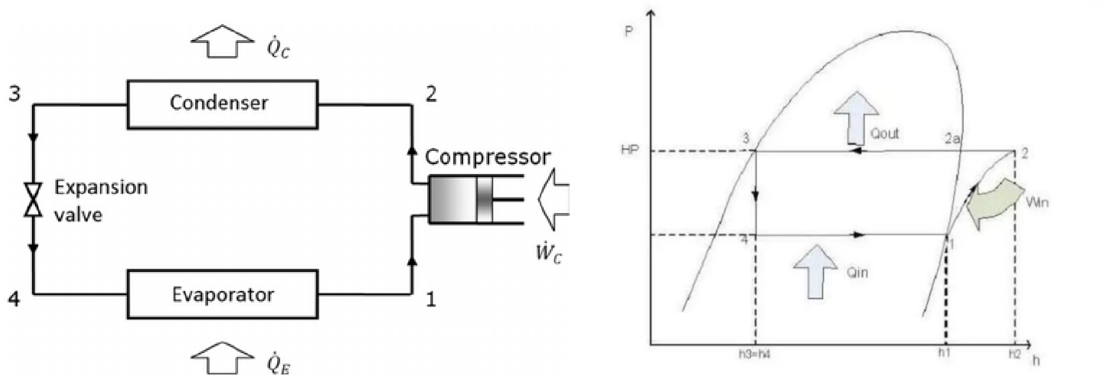

Figure 1. Refrigeration cycle (adapted from [6])

Energy analysis is a fundamental step in refrigeration systems' operational performance and efficiency evaluation. Key parameters often studied include suction pressure, cooling capacity (Q_e), heat rejection capacity (Q_c), and the coefficient of performance (COP) [7]. These parameters are derived from thermodynamic principles and can be calculated using specific relationships:

$$Q_e = h_1 - h_4 \quad (1)$$

where h_1 is the enthalpy of the refrigerant after the evaporator, and h_4 is the enthalpy of the refrigerant before the evaporator. The heat rejection capacity (Q_c) is calculated as:

$$Q_c = h_2 - h_3 \quad (2)$$

where h_2 is the enthalpy after the compressor and h_3 is the enthalpy before the condenser. System efficiency is evaluated using the Coefficient of Performance (COP), as written in Eq. (3).

$$COP = \frac{Qe}{W} \quad (3)$$

where W represents the work input required to operate the compressor.

These parameters affect not only energy efficiency but also the quality of the final product, such as the texture and stability of shortening oil. Therefore, optimizing operational parameters is a key strategy to improve system performance while maintaining product quality. For example, an increase in suction pressure can increase COP but may also reduce Q_e if the suction pressure becomes too high. This can result in less effective cooling, affecting the system's ability to maintain the optimal temperature during oil crystallization. A major challenge in operating refrigeration systems is finding the optimal balance among operational parameters such as suction pressure, temperature, and refrigeration flow rate [3]. Small changes in these parameters can affect both Q_e and Q_c, ultimately influencing the texture and penetration value (Pen.V) of shortening oil. This phenomenon underscores the importance of strict control and monitoring of operational parameters during the production process to achieve maximum energy efficiency without compromising the quality of the final product [4, 6].

2. Method

2.1. Tools and Materials

This research uses several main tools to test the performance of the refrigeration system in the production of shortening oil. The refrigeration system used consists of a compressor, condenser, expansion valve, and evaporator, which function to maintain the required temperature and pressure during the shortening oil production process. In addition, measurement instruments such as thermocouples are used to measure temperature, flowmeters to measure oil flow, and data loggers to record all measurement data automatically to ensure the accuracy and reliability of the observation results.

The main material used in this research is vegetable oil, which is a raw material to produce shortening oil. These vegetable oils are processed through several stages, including blending, heating, cooling, and texturizing, to produce shortening products that conform to quality standards. In addition, additives such as emulsifiers are used in the blending process to prevent oxidation that can damage the quality of the shortening oil, maintain the stability of the final product, and ensure optimal shelf life.

2.2. Shortening Oil Production Process

The shortening oil production process begins with mixing raw materials and additives such as emulsifiers to prevent oxidation that could reduce oil quality [8]. The mixing temperature typically ranges from 60 °C to 75 °C. After mixing, quality testing is conducted in the laboratory to ensure the shortening meets the specified standards. This testing includes measuring Free Fatty Acids (FFA) to indicate oil freshness, Iodine Value (IV) to assess unsaturation levels, Lovibond Color (LC) to determine color intensity, Moisture and Impurities (M&I) to evaluate purity, Peroxide Value (PV) to detect oxidation, Slip Melting Point (SMP) to identify the temperature at which solid fat transitions into a liquid state, and Solid Fat Content (SFC) to measure the proportion of solid fat at specific temperatures. If these quality parameters meet the desired standards, the process continues with preheating to elevate the oil temperature 15 to 20 °C above its melting point, followed by precooling until the temperature drops by 5 to 10 °C. The subsequent stage involves crystal formation in a cooling cylinder or Scraped Surface Heat Exchanger (SSHE) using refrigerant R22 as the cooling medium, aiming for crystal formation around 15 to 20% within the shortening oil. Once the desired texture is achieved, the shortening oil is packaged.

2.3. Energy Analysis Procedure

The energy analysis procedure is carried out by measuring temperature data, suction pressure, and discharge pressure on the compressor system using a display that is already installed in the refrigeration system. The data obtained is then analyzed using CoolPack software, which provides analysis results in the form of Q_e, Q_c, and COP values. In addition, measurements were also taken on the temperature of the oil entering and leaving the chemitator during the shortening production process to monitor the effectiveness of the refrigeration system in maintaining the quality of the final product.

2.4. Penetration Value of Shortening Oil

Penetration Value measurement of shortening oil is carried out using a penetrometer. The process begins by ensuring the tool is clean and calibrated according to the standard, then the shortening oil sample is placed in a flat container with a temperature according to the test conditions. The penetrometer needle is set just above the surface of the sample without applying initial pressure, then released so that the needle penetrates the sample under the influence of its weight or a certain additional load for a specified time, usually 5 seconds. The depth of penetration of the needle into the sample is measured using the scale on the tool in millimeters (mm). Measurements are taken at several different points to ensure representative results, and the average value is used as the final data. These results are used to evaluate the texture or consistency of the shortening oil based on predetermined quality standards [9].

3. Results and Discussion

Table 1 presents the observed data on the refrigeration system and production process, including compressor suction pressure, suction temperature, discharge pressure, discharge temperature, Q_c, Q_e, W, COP, cooling cylinder oil inlet and outlet temperatures, filling temperature, and penetration value (Pen.V) of the final product. This data illustrates the relationship between the operational parameters of the refrigeration system and its efficiency, as well as how the conditions of the production process affect the quality of the final product. The analysis of this table aims to evaluate the interaction between the parameters of the refrigeration system and the production process and their impact on product characteristics.

Table 1. Experimental Data

$P_{suction}$ (bar)	$T_{suction}$ (°C)	$P_{discharge}$ (bar)	$T_{discharge}$ (°C)	$T_{expansion\ valve\ R22}$ (°C)	Cooling Cylinder Outlet Oil Temp. (A1) (°C)	Cooling Cylinder Outlet Oil Temp. (A2) (°C)	$T_{filling}$ (°C)	Pen. V (mm/s)
1.2	27.4	12.6	76.4	-10	24.5	14.4	21.6	272.0
1.3	27.4	12.4	81.1	-10	25.7	14.5	21.8	278.0
1.4	27.6	13.1	83.2	-10	25.7	14.8	21.8	304.4
1.5	28.0	13.1	84.4	-9	25.6	14.9	21.8	308.0
1.6	28.0	13.5	86.0	-9	25.7	15.2	21.9	314.4

3.1. Effect of Suction Pressure on Q_e, Q_c, and W

Suction pressure plays a crucial role in refrigeration system performance, particularly influencing Q_e, Q_c, W, and COP. Simulations using Aspen Plus® and CoolPack indicate that increasing the suction pressure from 1. to 1.6 bar significantly enhances cooling capacity. Aspen Plus® recorded an increase in Q_e from 201.01 to 203.98 kJ/kg, whereas CoolPack showed an increase from 201.50 to 203.36 kJ/kg, attributed to the refrigerant's improved heat absorption capability (Figure 2). Condensation capacity (Q_c) remains relatively stable despite changes in suction pressure. Aspen Plus® displayed a consistent Q_c range from 225.81 to 225.57 kJ/kg, while CoolPack slightly decreased from 262.12 to 258.12 kJ/kg (Figure 3). Compressor work (W) decreases as suction pressure increases, as evidenced by simulations from Aspen Plus® from 25.28 to 22.86 kJ/kg and CoolPack from 60.58 to 54.76 kJ/kg. This decrease occurs due to the reduced pressure difference between the suction and discharge sides, aligning with findings by [6] (Figure 4). The COP increases with higher suction pressures in both simulations. Aspen Plus® shows an increase from 7.95 to 8.92, while CoolPack records an increase from 3.33 to 3.71. This indicates overall system efficiency improvement due to increased cooling capacity relative to compressor work (Figure 5). Optimizing suction pressure is essential for balancing energy efficiency and cooling process stability, as emphasized by [10]. Excessively high suction pressures can significantly reduce cooling capacity, whereas excessively low suction pressures increase energy consumption and accelerate compressor wear.

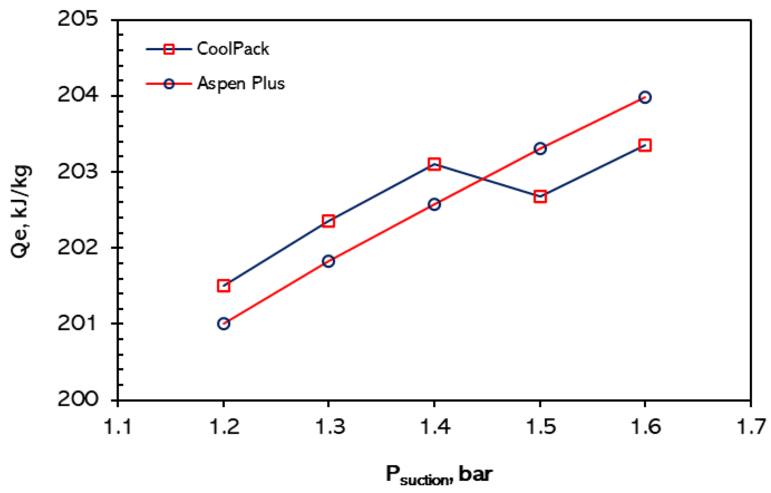

Figure 2. Effect of Suction Pressure on Q_e

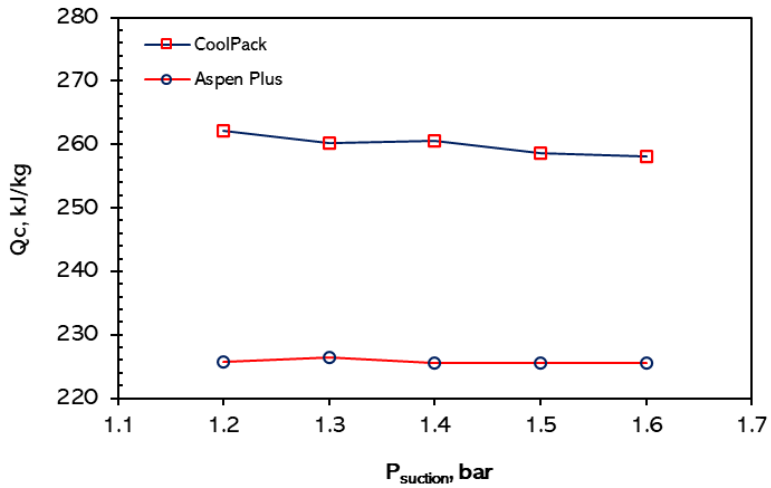

Figure 3. Effect of Suction Pressure on Q_c

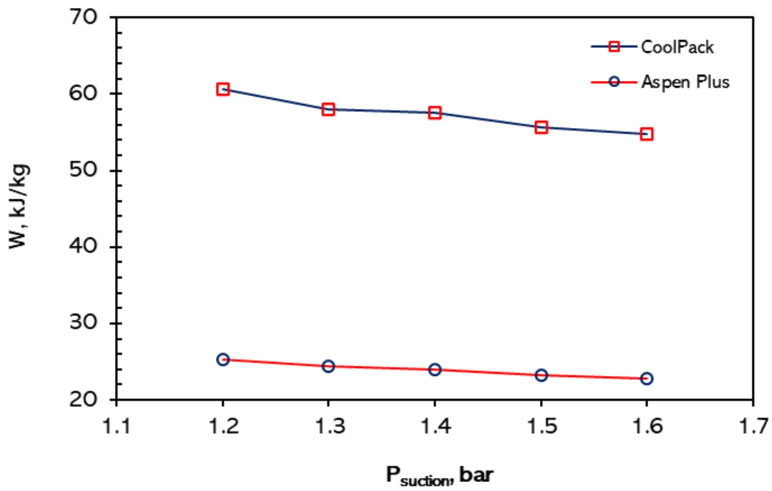

Figure 4. Effect of Suction Pressure on W

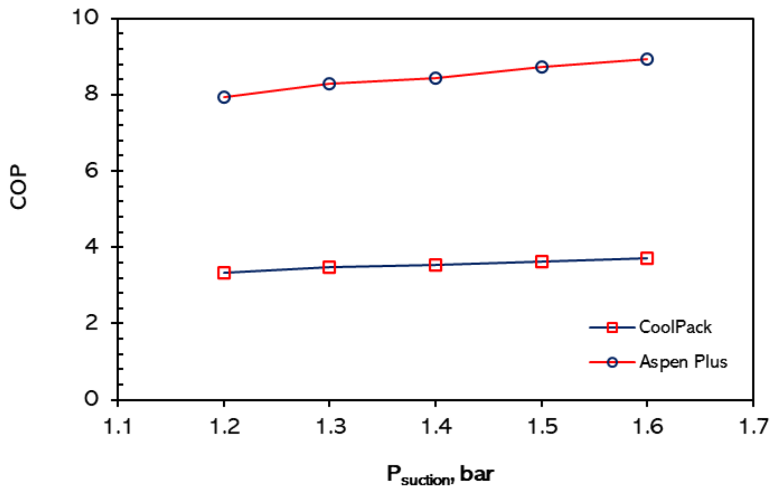

Figure 5. Effect of Suction Pressure on COP

3.2. Effect of Suction Pressure on Cylinder Cooling Oil Outlet Temperature

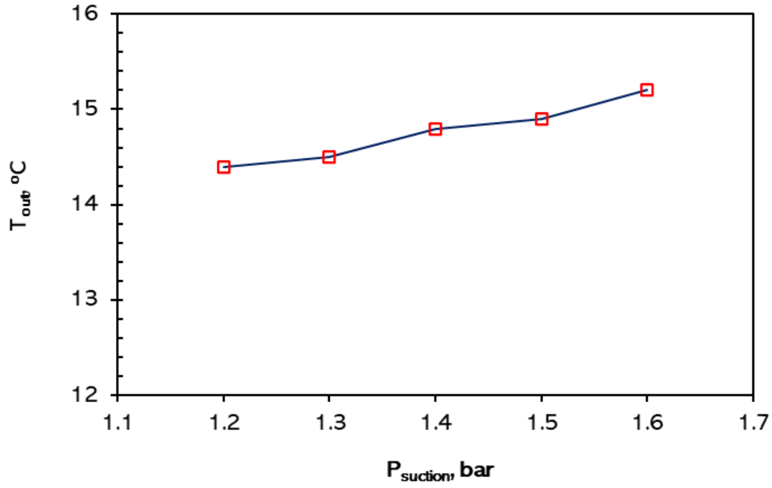

Figure 6. Effect of Suction Pressure on Cylinder Cooling Oil Outlet Temperature

Figure 6 shows a positive linear relationship between compressor suction pressure and the outlet temperature of cylinder cooling oil. An increase in suction pressure from 1.2 to 1.6 bar results in a rise in cooling oil temperature from 14.4 to 15.2 °C. This phenomenon occurs due to the higher density of the gas entering the compressor at elevated suction pressures, thereby increasing the compressor workload and generating more heat during compression. The heat produced is subsequently absorbed by the cooling oil, resulting in an elevated outlet temperature. Furthermore, increased suction pressure reduces the pressure difference between the suction and discharge sides, potentially decreasing cooling efficiency and contributing to the higher cooling oil temperature. These findings are consistent with the research conducted by [10], which showed that increasing suction pressure in a refrigeration system using refrigerant R290 improves cooling capacity but simultaneously increases compressor workload and heat generation during compression. Thus, optimizing suction pressure is crucial for maintaining thermal stability and overall efficiency in refrigeration systems.

3.3. Effect of Suction Pressure on Penetration Value

According to the graph, increasing compressor suction pressure significantly raises the penetration value of the product. The penetration value increased from 272 mm/s at a suction pressure of 1.2 bar to 314.4 mm/s at 1.6 bar, indicating that the product becomes softer with higher suction pressure. This occurs due to an increase in gas density entering the compressor, which raises the compressor's workload and generates additional heat during compression. Part of this heat is absorbed by the cylinder's cooling oil, increasing the oil outlet temperature and slowing down fat crystallization in the product, leading to a looser crystal structure and softer texture. These findings align with previous research by [10], which stated that increasing suction pressure elevates compressor workload and reduces cooling efficiency, impacting fat crystallization rate. Reduced cooling capacity resulting from higher suction pressures leads to looser crystal structures and higher penetration values. This study emphasizes the importance of optimizing suction pressure in refrigeration systems to control the final texture of shortening products according to desired quality standards.

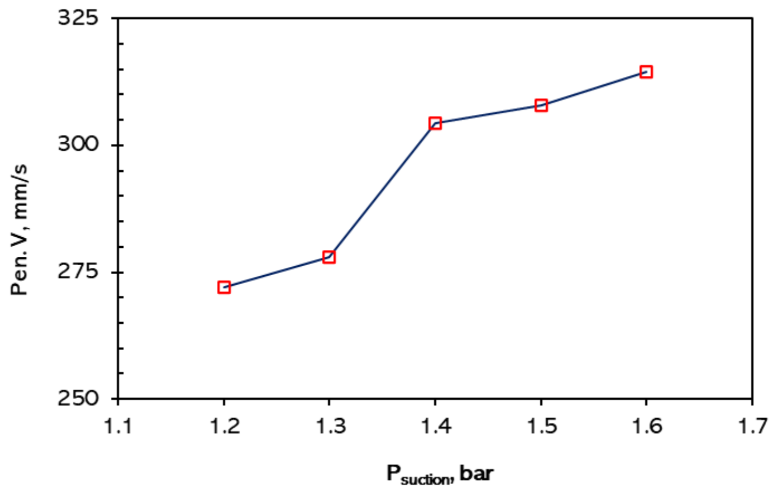

Figure 7. Effect of Suction Pressure on Penetration Value

4. Conclusions

Based on the simulation results of shortening oil production, it can be concluded that there is a significant relationship between energy and temperature parameters at various stages of the process. Energy analysis of the refrigeration system indicates that compressor suction pressure significantly affects system performance, as demonstrated by changes in Q_e, Q_c, and W. Increasing suction pressure from 1.2 to 1.6 bar led to decreased cooling and heat rejection capacities in simulations using Aspen Plus® and CoolPack software. Although there were differences in absolute values between Aspen Plus® and CoolPack due to differing calculation methods and assumptions, both showed similar trends concerning energy parameter changes in response to variations in suction pressure. In terms of product quality, an increase in suction pressure resulted in higher cooling cylinder oil outlet temperatures, increasing the shortening oil penetration value from 272 to 314.4 mm/s. This indicates that higher suction pressures produce softer product textures due to slower fat crystallization. Overall, this study provides important insights into optimizing operational parameters for shortening production, emphasizing the need to balance energy efficiency and product quality. Understanding the relationship between energy parameters and product characteristics serves as a valuable reference in designing and managing refrigeration systems to achieve products that meet market standards.

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