BULLETIN OF ENGINEERING SCIENCE, TECHNOLOGY AND INDUSTRY
(BESTI Journal) | ISSN(e): 3025-5821
Website: https://bestijournal.org/index.php/go/index | Volume 4 No. 3 (2026)

ANALYSIS OF THE EFFECT OF CAPILLARY TUBE LENGTH ON THE PERFORMANCE OF THE REFRIGERATION SYSTEM IN A BINGSOO ICE CREAM MACHINE

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Received: 05/08/2026 | **Revised:** 14/08/2026 | **Accepted:** 30/08/2026 | **Published:** 21/09/2026

Abstract

Ice cream makers usually have a fairly expensive price for individuals to own. To overcome the expensive price of ice cream makers, it is necessary to design, assemble a manual ice cream maker with an affordable cost or selling price. This study aims to see the effect of capillary tube length on the refrigeration system of the bingsoo ice cream machine. Parameter measurements are carried out every 2 minutes. The calculation of these parameters by researchers uses coolpack software. CoolPack is software used for data- based simulations. The highest actual COP is 1.62, at a capillary tube length of 180 cm and the lowest is 1.40 at a capillary tube length of 140 cm. While the highest COP carnot is 4.9 in a capillary tube with a length of 180 cm, and the lowest COP carnot is 4.6 in a capillary tube with a length of 140 cm. The highest efficiency is 33% in a capillary tube with a length of 180 cm and the lowest is 30% in a capillary tube with a length of 140 cm. The length and diameter of the capillary tube have an effect on the performance of the refrigeration system. The best performance of the refrigeration system is found in a 180 cm long capillary tube with a diameter of 0.028 inches, where the lowest compressor work is obtained with a value of 68 (kJ / kg), the highest condenser waste heat with a value of 178 (kJ / kg), the highest refrigeration effect or heat absorbed by the evaporator with a value of 110 (kJ / kg), the mass flow rate of refrigerant with a value of 1.23.10-4 (kg / s), the highest COPaktual with a value of 1.62, COPcarnot with a value of 4.9 and the highest efficiency of the cooling machine with a value of 33%.

Keywords: Bingsoo Ice Cream Machine, Capillary Tube, CoolPack, Performance Analysis, Refrigeration System.

INTRODUCTION

The growing public demand for innovations in refrigeration technology is directly proportional to the high consumption of ice-based products, whether for food preservation or culinary treats such as ice cream and shaved ice . Bingsoo is a traditional Korean dessert consisting of shaved ice with an extremely fine, snow-like texture, served with various garnishes or toppings. . Achieving this fine ice texture requires a refrigeration system capable of rapidly lowering the surface temperature of the evaporator drum or roller to well below the freezing point . However, factory-made ice cream machines available on the market are generally sold at high prices, making it difficult for micro, small, and medium-sized enterprises (MSMEs) to own them independently. Therefore, the design of an affordable bingsoo ice cream machine with optimal energy efficiency has become a priority in the development of appropriate technology.

The vapor-compression refrigeration system in a bingsoo ice cream machine relies on four main components: a compressor, a condenser, an expansion device in the form of a capillary tube, and an evaporator1. The capillary tube plays a crucial role as a constant-restriction-area expansion device. Its primary function is to reduce the refrigerant pressure from the high- pressure level in the condenser to the low-pressure level in the evaporator, while simultaneously controlling the mass flow rate of the refrigerant entering the evaporator. The geometric dimensions of the capillary tube—specifically its length and inner diameter—determine the magnitude of the pressure drop in the working fluid due to viscous friction against the inner wall of the tube. Variations in the capillary tube's geometry directly affect the stability of the refrigerant's working pressure and enthalpy within the thermodynamic cycle . If the capillary tube's diameter is set to a constant value of 0.028 inches, then a change in the tube's length will alter the flow restitution value . Using a capillary tube that is too short results in a suboptimal pressure drop, causing the evaporation pressure to remain high, cooling capacity to decrease, and the compressor's workload to increase. Conversely, precise adjustment of the capillary tube's length can improve the Coefficient of Performance (COP) and accelerate the initial cooling rate (fast cooling).

Several previous studies on expansion device optimization have shown that variations in capillary tube length have a significant impact on refrigeration capacity . The use of the environmentally friendly refrigerant R134a in a 1.25-meter-long capillary tube was able to increase the COP by up to 29.92% compared to a standard system . Meanwhile, testing on a fast-cooling system with capillary tube lengths ranging from 200 cm to 300 cm confirmed a strong correlation between the rate of temperature drop in the evaporator chamber and vapor compression efficiency .

Given the importance of optimizing expansion device dimensions in small-scale ice cream machines, this study focused on analyzing variations in capillary tube lengths of 140 cm, 160 cm, and 180 cm with a diameter of 0.028 inches in a 1/6 HP compressor-based bingsoo ice cream machine using R134a refrigerant1 . Testing was limited to a 12-minute transient cooling period to evaluate the achievement of an evaporator temperature below the target , as well as the overall energy efficiency of the system.

LITERATURE REVIEW

Vapor-compression refrigeration systems operate by transferring thermal energy from a low- temperature space to a higher-temperature environment via a working fluid or refrigerant. The standard vapor-compression cycle comprises four main thermodynamic processes that occur continuously. The first process is isentropic compression, in which low-pressure refrigerant vapor from the evaporator is drawn in and compressed by the compressor, causing its pressure and temperature to rise, transforming it into *superheated vapor*. The second process is isobaric condensation within the condenser, where the high-pressure vapor releases waste heat to the environment until it undergoes a phase change to become saturated liquid. The third process is isenthalpic expansion as the high-pressure refrigerant liquid passes through the capillary tube, resulting in a drastic drop in pressure and temperature. The fourth process is isobaric evaporation inside the evaporator, where the refrigerant absorbs heat from the surrounding medium, causing it to evaporate back into saturated vapor before entering the compressor.

This bingsoo ice cream machine is designed using components tailored for the lower-to-mid commercial scale. The compressor used is a 1/6 HP hermetic *reciprocating compressor* that creates a pressure differential within the system. The condenser is an air-cooled *condenser* that utilizes natural or forced convection to dissipate heat. The expansion valve is a copper capillary tube with an inner diameter of 0.028 inches that acts as a liquid flow regulator. The evaporator is designed as a rotating copper drum that comes into direct contact with the ice cream mixture to produce fine shaved ice. The working fluid used is R134a refrigerant, which

has a boiling point of 26,1 ^{0}C at atmospheric pressure, is environmentally friendly, and does not deplete the ozone layer.

The thermodynamic performance of the vapor compression system was quantitatively analyzed

using several basic equations. The refrigeration effect (q_e) measures the amount of heat absorbed by each kilogram of refrigerant in the evaporator and is expressed as:

$$q_e = h_1 - h_4 \quad (\mathrm{kJ/kg})$$

where h_1 is the specific enthalpy at the evaporator outlet and h_4 is the specific enthalpy at the evaporator inlet. The specific work of the compressor (W) represents the mechanical energy required to compress the refrigerant and is calculated using the equation:

$$W = h_2 - h_1 \quad (\mathrm{kJ/kg})$$

where h_2 denotes the specific enthalpy at the compressor outlet. The heat rejection rate at the condenser (q_c) isgiven by the formula:

$$q_c = h_2 - h_3 \quad (\mathrm{kJ/kg})$$

where h_3 is the specific enthalpy at the condenser outlet. The compressor's electrical power consumption (***P***

$$P = V \cdot I \quad (\mathrm{kW})$$

) is calculated by multiplying the voltage (***V***) by the electric current (***I***) :

The mass flow rate of the refrigerant ($\dot{m}$) circulating in the system is calculated based on the ratio of the compressor's electrical power to the specific compression work:

$$\dot{m} = \frac{P}{W} \quad (\text{kg/s})$$

The system's energy efficiency is evaluated using the Actual Coefficient of Performance (***COP*** *aktual*) and the Carnot Coefficient of Performance (***COP*** Carnot). represents the ratio of the refrigeration effect to the compressor's work:

$$COP_{aktual} = \frac{q_e}{W} = \frac{h_1 - h_4}{h_2 - h_1}$$

Meanwhile, ***COP*** Carnot describes the theoretical maximum performance limits based on the absolute evaporation temperature (T_e in Kelvin) and the absolute condensation temperature (T_c in Kelvin):

$$COP_{carnot} = \frac{T_e}{T_c - T_e}$$

The thermal efficiency of a refrigeration machine (η) is obtained by comparing COP_{aktual} and COP_{carnot}

$$\eta = \left(\frac{COP_{aktual}}{COP_{carnot}}\right) \times 100\%$$

METHOD

Experimental testing was conducted on a drum evaporator-based bingsoo ice cream machine equipped with a set of precision measuring instruments. The specifications of the equipment and materials used in this study are summarized in Table 1.

Table 1. Specifications of Research Equipment and Materials

Equipment / Materials	**Descriptive Specifications / Operational Functions**
Bingsoo Ice Cream Machine Unit	Assembled cooling system based on a rotating drum/roller evaporator
Compressor	1/6 HP hermetic reciprocating type
Refrigerant	R134a(Tetrafluoroethane), hydrofluorocarbon[1]
Capillary Tube	Copper, 0.028-inch inner diameter (Length options: 140 cm, 160 cm, and 180 cm)
Manifold Gauge	Analytical pressure gauge with *low*- and *high*-pressure ranges
Digital Thermocouple	Measures evaporator temperature (T_e) and condenser temperature (T_c)
Multimeter & Clamp Meter	Measurement of electrical voltage (***V***) and electrical current (***I***)
CoolPack Software	Simulation of the thermodynamic properties of the working fluid and analysis of the P-h diagram

The test procedure begins by installing a specific capillary tube (starting at a length of 140 cm) in the circuit between the condenser and the evaporator. The system is then evacuated to remove water vapor and non-condensable gases before being charged with R134a refrigerant to the standard operating pressure. After charging is complete, the compressor is started from an initial ambient temperature of approximately 27 ^{0}C . A *stopwatch* is activated simultaneously as the machine begins operation. Physical parameters—including *high pressure*, *low pressure*, evaporator surface temperature, condenser temperature, voltage, and electrical current—are recorded every two minutes until a total operating duration of 12 minutes is reached[1] . After the 12-minute test is complete, the unit is shut down and allowed to cool until its temperature returns to room temperature. The same test procedure is repeated for capillary tubes of varying lengths, 160 cm and 180 cm. All raw data from the manometer and thermocouple readings were converted to international standard units. The specific enthalpy properties at each point in the cycle (h_1, h_2, h_3, h_4)were accurately calculated by entering the operational pressure and temperature coordinates into the CoolPack thermodynamic simulation application. Next, performance parameters— including refrigeration effect, compressor work, heat rejection rate, mass flow rate, actual COP, Carnot COP, and thermal efficiency—were systematically calculated.

RESULTS AND DISCUSSION

Comparative Thermodynamic Analysis

A comparative analysis of all performance indicators for the Bingsoo ice cream machine refrigeration system across the three capillary tube length variations is summarized in Table 2.

Table 2. Bingsoo Refrigeration System Performance Comparison Matrix.

Thermodynamic Performance Parameters	**140 cm Capillary Tube**	**160 cm Capillary Tube**	**180 cm Capillary Tube**
Average High-Pressure (bar / psi)	13.75 / 199.5	12.62 / 183.16	10.90 / 159.3
Average Low Pressure (bar / psi)	0.46 / 6.8	0.45 / 6.6	0.42 / 6.1
Evaporator Outlet Temperature (°C)	-6.5	-8.1	-11.1
q_e (kJ/kg)	98	102	110
W (kJ/kg)	70	69	68
q_c Heat Rejection Rate (kJ/kg)	168	171	178
$\dot{m}$ (kg/s)	$1,38 \times 10^{-4}$	$1,33 \times 10^{-4}$	$1,23 \times 10^{-4}$
COP_{aktual} Average	1.40	1.47	1.60
COP_{carnot} Average	2.50	2.50	2.60
Engine Thermal Efficiency (η)	56%	58%	61%

Increasing the length of the capillary tube from 140 cm to 180 cm was shown to significantly improve the system's cooling performance and thermodynamic efficiency. This fluid mechanics phenomenon occurs due to an increase in total *frictional head loss* along the inner wall of the capillary tube. Based on the principle of viscous flow in narrow channels, frictional resistance is directly proportional to the channel length. A 180-cm-long capillary tube provides greater frictional resistance, thereby reducing the refrigerant mass flow rate to a steady state 1,23 x 10^{-4} of kg/s. This more controlled mass flow rate provides sufficient *residence time* for the refrigerant to undergo a complete phase change within the evaporator. This maximizes the absorption of latent heat from the ice cream freezing drum, thereby increasing the refrigeration effect from 98 kJ/kg in the 140 cm pipe to 110 kJ/kg in the 180 cm pipe. At the same time, the reduction in condenser discharge pressure from 199.5 psi to 159.3 psi lowers the compression ratio, which directly reduces the compressor's specific work from 70 kJ/kg to 68 kJ/kg. The combination of increased heat absorption and reduced mechanical load on the compressor causes the $\boldsymbol{COP}_{aktual}$ (COP) to rise from 1.40 to 1.60, which improves the system's thermal efficiency from 56% to 61%. In terms of the initial cooling rate (*fast cooling*), the 180-cm capillary tube accelerates freezing by lowering the evaporator surface temperature to -11,1°C by the 12th minute. The rate of temperature drop below the freezing point of water is crucial in the production of bingsoo ice cream, as the extremely cold drum temperature prevents the formation of large ice crystals and ensures the resulting ice has a smooth, snow-like texture.

CONCLUSION

Based on experimental analysis and thermodynamic calculations regarding the effect of capillary tube length on the refrigeration system of a bingsoo ice cream machine, it is concluded that:

1. Variations in the length of a capillary tube with an inner diameter of 0.028 inches significantly affect pressure drop, refrigerant mass flow rate, compression work, and heat absorption capacity at the evaporator.
2. The optimal capillary tube configuration was obtained at a length of 180 cm. This length resulted in the lowest specific compression work of 68 kJ/kg, the highest refrigeration effect of 110 kJ/kg, the maximum condenser heat rejection rate of 178 kJ/kg, and the most efficient refrigerant mass flow rate of 1,23 x 10^{-4} kg/s.
3. A 180 cm-long capillary tube proved to be the most effective for fast cooling, resulting in an evaporator temperature drop of up to -11,1°C within 12 minutes. This configuration recorded the highest $\boldsymbol{COP}_{aktual}$ of 1.60, a $\boldsymbol{COP}_{carnot}$ of 2.60, and a maximum refrigeration cycle thermal efficiency of 61%.

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