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Original Article

Impact of Warming on Heat and Mass Transfer in Chilled Sweetened Carbonated Beverages: A Thermodynamic Study

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Abstract - *This investigation explores the mass and heat transfer mechanisms governing warming of a chilled Sweetened Carbonated Beverage (SCB) bottle for various ambient conditions. Two primary phenomena are identified as contributing factors to the warming process: Mass Transfer by Condensation Driven: The temperature difference between the external layer of the cold bottle and the ambient air practice resulting in the condensation of the water droplets from the air to the surface of the cold bottle. The warming effect from this mass transfer process is large. Ambient Heat Transfer: In addition to free convection, the air's natural circulation is driven by temperature differences, and the condensation of water vapor helps direct the heat from the external environment to the bottle. These phenomena are concomitant and affected by external environmental temperature and humidity. In this work, the mass transfer and heat coefficients associated with these phenomena were evaluated using a novel theoretical experimental methodology. Measuring the temperature rise and mass of condensed water in SCB bottles over time, subjecting the bottles to both conditioned and unconditioned temperature and humidity fluctuations is controlled. The results show that the convective HT coefficient significantly depends on the adjacent temperature and relative humidity. Interestingly, temperature appears to have a more substantial impact on the mass transfer coefficient. This research serves as an important guide to the factors that control the temperature of SCB bottles and paves the way for designing more accurate models to predict bottle temperature changes across various environmental settings.*

Keywords - *Mass transfer, Heat transfer mechanisms, Warming of chilled beverages, SCB, Warming effect.*

1. Introduction

Due to its concern for maintaining beverage quality, retention of sensory attributes, and carbonation stability, the thermal behaviour of chilled Sweetened Carbonated Beverages (SCBs) during warming under ambient conditions is a critical area for study. SCBs are very susceptible to environmental conditions, and temperature regulation is a huge determinant of satisfaction. Despite their widespread consumption and industrial significance, research on SCBs has chiefly studied individual heat or mass transfer aspects without considering the coupled interplay between the two processes. At the same time, the quantitative importance of environmental variables, such as relative humidity and ambient temperature, in the warming process is underexplored and constrains the sophistication of predictive models applicable across a wide range of conditions.

Current models for predicting SCB warming are simple and do not include the coupled influence of condensation-driven mass transfer and natural convection. Existing studies have investigated these mechanisms singly, yet their combined effect in real world scenarios is uncertain. Also, the heat and mass transfer from bottle surface properties, including wettability and dynamics of condensation film formation, have not been thoroughly studied. The lack of precise tools to model SCB warming inhibits the development of useful tools to model advances in optimizing storage, transportation and handling strategy.

1.1. Novelty of the Work

This study develops a new theoretical, experimental framework to remedy the weaknesses of extant models. Unlike previous research, which typically uses empirical models with limited generalizability, this work relies on a coupled heat and mass transfer analysis that considers critical environmental variables such as ambient temperature and relative humidity. The study evaluates heat and mass transfer coefficients quantitatively and mainly, as they relate to one another under different conditions. This research considers the role of surface property (wettability, film dynamics) in a more holistic explanation of the SCB energy warming process. This innovative method improves the prediction performance of such predictive models and provides practical implications for thermal management in the beverage industry.

1.2. Comparison with Existing Research

Past research has concentrated mainly on using simplified Newtonian models or correlations of Nusselt numbers to describe natural convection. However, these studies do not even account for the major contribution of the condensation-driven mass transfer, which has been intuitively considered in the context of surface condensation phenomena. Additionally, few studies have identified the environmental parameters influencing the coupled HMT process, such as temperature and humidity.

However, the quantitative effect of such parameters on the coupled HMT process has not been understood well. In terms of completing these gaps, this study combines controlled experimental data with a total analysis that includes natural convection and condensation processes while contemplating their interaction in a real environment. Moreover, the work goes beyond current approaches and includes surface characteristics and condensation dynamics to provide new insights into the conditions in SCBs that were not previously considered. The existing literature on HMT processes in SCBs is reviewed, and a fragmented understanding of these processes is shown. Some studies have proven the effects of the ambient condition on heat transfer coefficients and have failed to consider their combined effect on the coupled transfer mechanisms.

The role of condensation-driven mass transfer is admitted but not quantitatively evaluated. In this work, we further develop these foundations, and by employing experimental validation and theoretical modeling, we address these gaps. Integrating a coupled heat and mass transfer framework, this study provides a more comprehensive view of the warming dynamics of SCBs, bridging empirical findings with practical applications. The key gap in our knowledge of the coupled HMT processes responsible for SCB warming under changing environmental conditions is addressed in this study.

The research extends existing findings by combining theoretical insights, experimental validation, and novel considerations, including surface wettability and condensation film dynamics. The actionable insights from these contributions span the development of efficient storage and handling strategies to promote the improved quality control and preservation of SCBs in the use of real systems.

1.3. Modeling Heat Transfer and Condensation in a Warming SCB Bottle: A Deeper Dive

The subject of this document is the theoretical framework of modelling the HT processes which contribute to the warming of a Sweetened Carbonated Beverage (SCB) bottle. The two identified mechanisms are natural convection and condensation, dependent on the humidity level [1] and the ambient air temperature [2].

1.3.1. Natural Convection

Beyond a Simple Approach

Newton's Law of Cooling provides a starting point for estimating heat transfer caused by natural convection, but it has limitations [3]. We expand the model for greater accuracy here.

Nusselt Number (N_{Nu})

It is a dimensionless variable, convective HT coefficient (h_{conv}), which depends only on the thermal conductivity of the air (k), characteristic length of the bottle (L) such as its diameter, and fluid characteristics (N_{Pr}, Prandtl number) [4] [5]. The correlations for h_{conv} [6] are conserved for a wide range of geometries and flow regimes, allowing for more exact computation of (N_{Nu}).

Boundary Layer Theory

According to this theory, a thin layer of air develops in contact with the bottle surface, where viscous factors are the main mechanism of flow [7]. The equations governing fluid flow and HT in the boundary layer are then calculated, allowing a more precise temperature profile to be obtained around the bottle [8].

Computational Fluid Dynamics (CFD)

CFD simulations can be an alternative where the geometries or flow conditions are complex [9]. The equations that govern the fluid flow and heat transfer are solved numerically over the entire domain of the bottle, giving a detailed picture of where the temperature distribution and heat transfer rates take place in the domain [10].

1.3.2. Condensation

Unveiling the Complexity

A basic framework to understand condensation is given using the mass transfer equation. The actual process, however, is more complicated [11].

Surface Wettability

The way water vapor condenses and spreads (on the bottle surface, e.g. glass or plastic) depends on the bottle surface wettability [12]. A more hydrophilic (water loving) surface should promote an entire continuous liquid film formation, but a hydrophobic (water repelling) surface could be responsible for discrete droplet formation [13].

Film Dynamics

Surface tension and gravity can cause the condensed liquid film to demonstrate complicated flow patterns. This flow can influence the rate of mass transfer and heat transfer to the bottle surface [14].

Evaporation

Some condensed liquid may evaporate back into the air if the bottle's surface temperature rises because of condensation [15]. A complete picture of this evaporation process needs to be factored into the model.

Modeling Approaches for Condensation
a) Empirical Correlations

Mass transfer coefficient (Km) is correlated empirically with air properties, flow conditions, and bottle geometry. Correlations with these can be used to estimate the condensation rate [19] [20].

b) CFD Simulations with Phase Change Models

Having phase change models in advanced CFD simulations in which water vapor transitions between gas and liquid during condensation [23]. These models necessitate providing exact information about surface properties and material interactions.

1.3.3. Coupled Heat and Mass Transfer

Condensation can release enough heat to affect the air's buoyancy-driven flow around the bottle or bottle and how fast natural convection will pick up heat. Therefore, it is required that the interaction between these phenomena is included in a coupled-mass and Heat Transfer model.

1.4. Conclusion: Towards A Comprehensive Model

Incorporating the above concepts allows us to build a better model for simulating the warming of an SCB bottle. This model would likely involve knowing what formulas rule out heat transmission and fluid movement in regard to the bottle, Nusselt number, or CFD simulations.

The MT of water vapor from the air to the bottle surface is modelled with a mass transfer equation, accounting for surface wettability and film dynamics. Modelling how latent heat released during condensation changes the temperature profile around the bottle. A detailed model, helped by this, resulted in a more accurate representation of the processes of heat transmission and condensation of SCB bottles, which would help us understand the processes that respond to the rate of warming.

2. Exploring the Equations: Natural Convection and Condensation

Depending on the scenario, we can examine the equations for natural convection and condensation and investigate the fundamental ideas.

2.1. Natural Convection

The exact form of the Equation may involve some serious relationship, but a rough idea of what it might be can be useful if we understand its core idea. One possible example of natural convection heat transfer is following Newton's Law of Cooling.

2.2. Newton's Law of Cooling

This equation's natural convection heat transfer rate is the simplified equation to estimate it. It will talk about the heat transfer rate.

$$Q = N_{Nu} = h_{conv} * A_0 * (Tb - Ta) \qquad (1)$$

Where, Q = heat transfer per unit time, N_{Nu} = This number characterizes the HT by convection relative to that by conduction, Nusselt number (dimensionless). Convection heat transfer coefficients, h_{conv} (W/m²/K). Here is the thermal heat transfer due to convection. Factors that include the temperature difference, fluid properties and bottle geometry need to be somehow retrieved from it, ranging from correlations and tables versus it depends. It shows the efficiency with which heat from the bottle surface to the ambient air is lost through natural convection [16].

A_0 = This is the total area of the bottle exposed to the surrounding air, Tb- Temperature of the bottle surface (°C), Ta -Temperature of the surrounding air or ambient air (°C). This equation suggests that the rate of heat transfer due to natural convection (N_{Nu}) is proportional to the following factors: Convection heat transfer coefficient (h_{conv}): Higher (h_{conv}) signifies more efficient heat transfer from the air to the bottle, Surface area (A_0): A larger surface area allows for more heat exchange with the surrounding air, Larger Temperature difference ($Tb - Ta$) drives a stronger heat transfer from the warmer air to the colder bottle.

However, determining the specific value of (h_{conv}) requires more advanced models or empirical correlations considering the complex flow patterns of natural convection around the bottle.

Condensation: Similar to the approach for natural convection, the Equation might be related to the MT of water vapor from the air to the bottle surface. Here is a simplified representation based on the analogy with Newton's Law of Cooling:

$$N_{sh} = K_m * A_0 * (Ca - Cs) \qquad (2)$$

Where N_{sh} is Sherwood number (dimensionless) characterizes the mass transfer relative to diffusion [17], K_m is Mass transfer coefficient (m/s) reflects the efficiency of the mass transfer due to convection. The concentration of water vapor Cs at the bottle's surface (kg/m³) and Ca in the air (kg/m3) (as Ca is usually assumed zero as a result of condensation) are the factors for this.

This equation suggests that the rate of mass transfer due to condensation (N_{sh}) is proportional to the following factors: Mass transfer coefficient (K_m): More transfer of water vapor molecules from the air to the bottle surface is shown by a higher K_m. Surface area (A_0**):** Similar to natural convection, a larger surface area would allow more condensation to occur. Concentration difference (Ca-Cs): The higher condensation rates are due to a larger concentration difference between water vapor in the air and at the bottle surface.

The specific value of K_m cannot be determined without the use of advanced models and empirical correlation to account for specific flow patterns and boundary layer effects near the bottle surface.

Simplified equations in heat transfer and mass transfer processes provide a basic knowledge of how energy or mass flows in a system. These equations show the heat transfer, which is the flow of thermal energy. They also show mass transfer, the movement of particles of a fluid or a solid medium. In particular, they address important factors, such as temperature gradients, material properties, and fluid flow, to address the complex, interdependent processes controlling these systems conceptually. While we have simplified these equations, they help predict system behaviour and design efficient energy solutions.

For natural convection and condensation processes, real world models are more complex than simplified equations can account for. In addition to the fluid properties (viscosity and density), system geometry, and turbulence effects, these models must be included. In natural convection, density variations occur due to a temperature difference, forcing buoyancy forces to carry the fluid motion, and condensation introduces phase change dynamics.

In some of these systems, the warming is not the simple result of one of the mechanisms alone but of the combination of natural convection and condensation, and this often requires coupled differential equations for precision predictions.

Finally, the general understanding of these equations results in understanding the basis of the natural convection and condensation in warming the SCB bottle. The warmers' warming rate depends on factors such as air temperature, relative humidity, and bottle geometry, and these heat and mass transfer phenomena.

$$q_{cond} = h_{cond} A_0 (Ts - Ta) \quad (3)$$

$$q_{cond} = m_{cond} \triangle H_{cond} \quad (4)$$

3. Materials and Methods: Evaluating Heat and Mass Transfer during a Chilled SCB Bottle's Warming

This section describes the experimental apparatus and procedure used to study the total mass and heat transfer mechanism for a chilled Sweetened Carbonated Beverage (SCB) bottle in different environmental conditions.

3.1. Experimental Apparatus

Condensate Collection Tray, SCB Bottle, High Precision Analytical Balance (1 ± 0.01g), RTD (Resistance Temperature Detector), Thermometer (-10 to 100°C), digital timer, calibrated standard weights of 0.01g to 1kg for calibration, certified calibration bath at 0°C and 50°C, and reference thermometer 0°C and 100°C, and reference hygrometer to within ±1% relative humidity, and ±0.5 degree C.

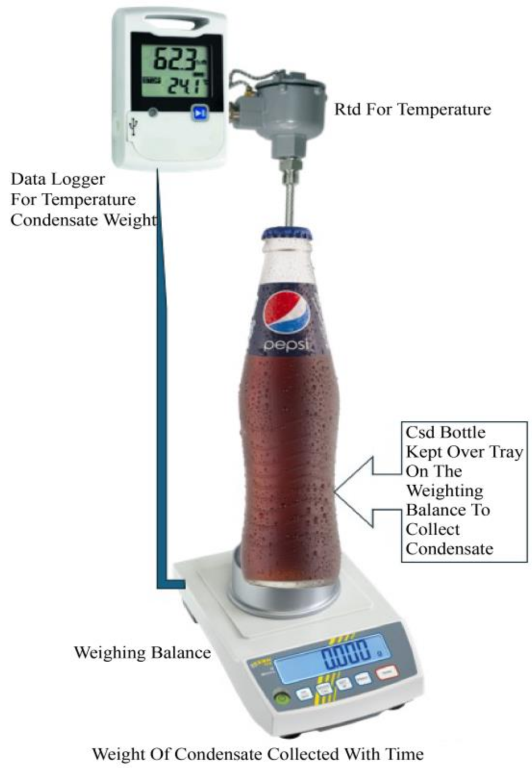

Fig. 1 Measure to condensate, temperature and time experiment module SCB PET bottle

Instrument Calibration is the first priority of our study. Analytical Balance was calibrated using standard weights to ensure accuracy within ±0.01 g.

Calibration was performed before and after each set of measurements. To verify accuracy, the RTD Thermometer was calibrated using a certified calibration bath at 0°C and 100°C.

Additional validation was performed by comparing the readings against a reference thermometer. Controlled Environment Sensors are temperature and humidity sensors in the environment chamber calibrated using a standard reference hygrometer to ensure measurement accuracy within ±1% relative humidity and ±0.5°C.

3.2. Experimental Procedure

3.2.1. Pre-Cooling the SCB Bottle

A whole bottle of SCB was placed in a refrigerator until its temperature reached a uniform value of 6°C. The bottle was equipped with a cap-mounted RTD thermometer to monitor the internal temperature throughout the experiment.

3.2.2. Initial Measurements and Setup

The chilled SCB bottle was carefully transferred to a controlled environment chamber (balance room) for the experiment. The bottle's surface was meticulously dried using a lint-free cloth to remove any residual moisture that could affect the condensate mass measurements.

3.2.3. Data Collection

The pre-cooled SCB bottle was positioned on the condensate collection tray, previously placed on the analytical balance platform. After subsequent measurements, the analytical balance and timer were reset to zero. The starting temperature and mass of accumulated condensate measurements followed this. Surface temperature readings were taken regularly to a temperature rise of 0.50°C in the bottle's temperature. The analytical balance was the instrument used to measure the mass of condensate. Weights of the tray before and after second intervals were recorded, and the additional difference over each interval was calculated to find the accumulated condensate. The sequence of this data collection process continued without interruption until the temperature of the SCB bottle reached the temperature of the controlled environment chamber.

3.2.4. Environmental Monitoring

Calibrated instruments were used to measure the temperature, RH, and altitude of the surrounding environment in the controlled environment chamber in conjunction with the bottle's temperature and condensate mass data. Real-time temperature and RH readings were available from the chamber sensors. Before and after each experiment, these readings were verified against independent instruments.

3.2.5. Multiple Trials

To ensure reproducibility and reliability, the entire experimental procedure was repeated several times with controlled variations of ambient temperature and relative humidity conditions. Additional trials were conducted to test the generality of the findings: variations in bottle geometry and material.

Additional analysis was performed on the specific details of these conditions in another table. The repetition also allowed us to measure how these environmental factors affected the warming process of the SCB bottle. The experiment aimed to understand the interaction between heat and mass transfer phenomena in this process.

Table 1. Temperature Ambient and Relative Humidity (RH) condition

Assay	Ta in °C	RH
1	22	48%
2	24	32%
3	28	35%
4	19	68%
5	19	85%

3.2.6. Measurement Techniques

Beverage Temperature Measurement

The RTD thermometer placed in the bottle cap made Precise surface temperature readings. Errors arising from manual recording were minimized by digitizing measurements.

Mass Transfer Measurement

The mass of condensed water in the condensate collection tray was determined by weighing it at each interval. Subtraction of the previous reading from the current reading allowed for exact condensation over time and incremental changes in mass were calculated.

Environmental Condition Monitoring

At the beginning and end of each trial, the temperature and humidity readings in the chamber were checked against independent instruments. They had any deviations corrected promptly to keep things consistent.

Data Recording and Analysis

The time, surface temperature, and mass of condensate were recorded for each trial. Polynomial curve fitting was applied to the data to model M(t) (condensed mass as a function of time) and T(t) (surface temperature as a function of time).

Additional Experimental Notes

Latent Heat of Vaporization ΔH_{cond} (2257 kJ/kg) was used for calculations, adjusted for ambient pressure conditions, if any.

Surface Area Calculation

The external surface area of the SCB bottle was calculated geometrically based on its dimensions.

Concentration Gradients

The Clausius-Clapeyron and Antoine equations were employed to calculate vapor pressures and concentration gradients for condensation modeling.

4. Determination of Condensation Heat Transfer Coefficient (h_{cond}) and Mass Transfer Coefficient (K_m)

The provided information outlines the approach to determine key parameters involved in condensation on a bottle surface:

4.1. Mass of Condensed Water $M(t)$ and Condensate Flow Rate (m_{cond})

The text describes $M(t)$ as a function of time obtained by fitting a polynomial equation to experimental data. To determine (t), conducted experiments measuring the mass of condensed water at various time points.

Subsequently, fitting an appropriate polynomial to this data will yield the desired function $M(t)$. Condensate flow rate (m_{cond}) can be calculated by taking the derivative of

$M(t)$ to time: $mcond = \frac{d}{dt}M(t)$

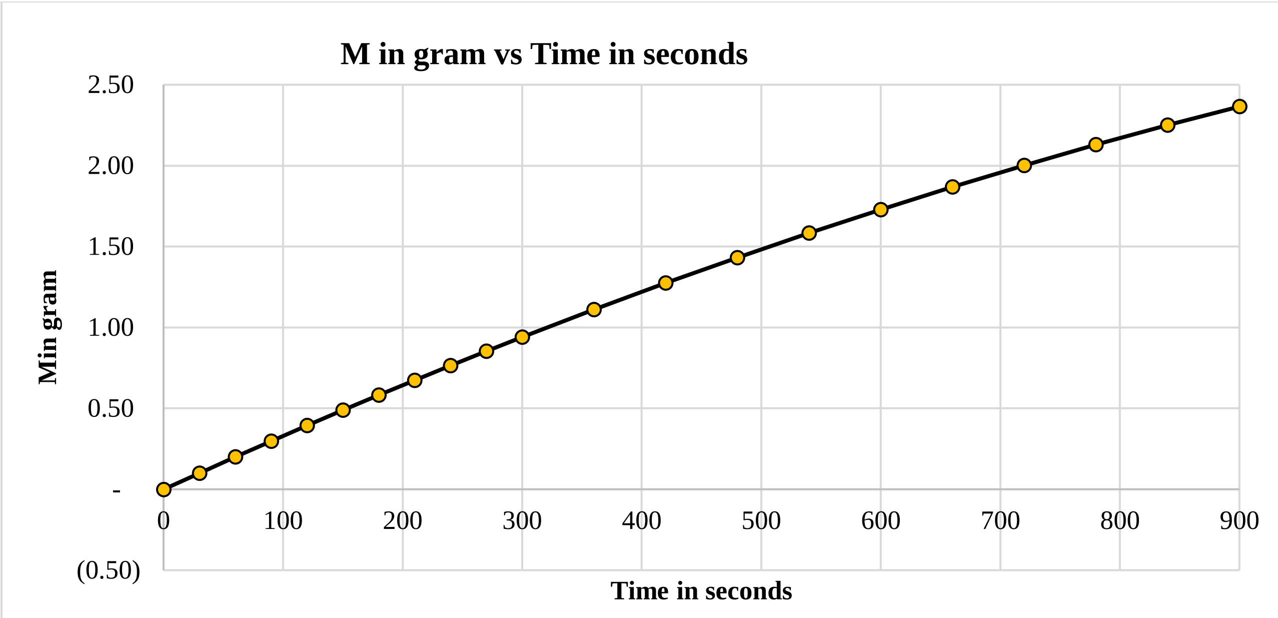

Fig. 2 M in gram versus time in second

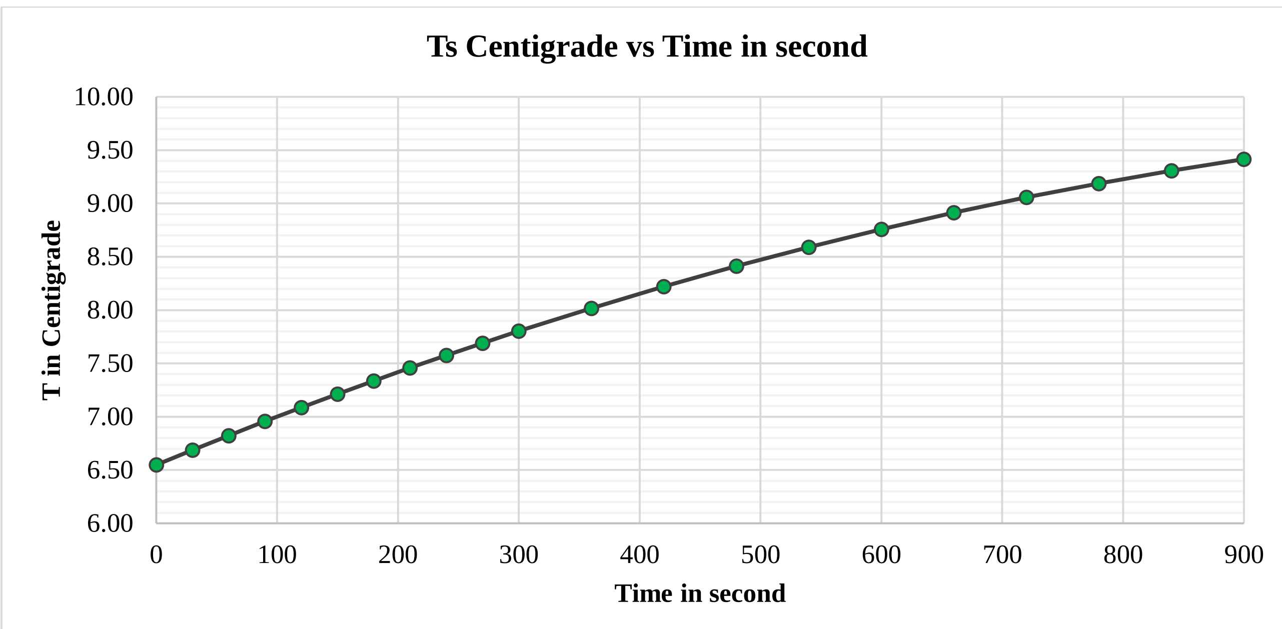

Fig. 3 T in Centigrade versus time in second

$$M = -8.4791 * 10^{-7}t^2 + 3.3916 * 10^{-3}t - 8.3503 * 10^{-4} \quad (5)$$

$$T = -1.6599 * 10^{-6}t^2 + 4.6799 * 10^{-3}t + 6.54801 \quad (6)$$

4.2. Condensation Heat Transfer Coefficient (h_{cond})

An equation is provided that relates $hcond$ to other measurable parameters:

$$h_{cond} = m_{cond} * \frac{\triangle H_{cond}}{A_0 * (Ts - Ta)} \quad (7)$$

Where $\triangle H_{cond}$: Latent heat of vaporization of water (~2257 kJ/kg at standard conditions), A_0: Surface area of the bottle (measurable),Ta : Air temperature surrounding the bottle (measurable with a thermometer), Ts : Surface temperature of the bottle as a function of time (requires measurement with a temperature sensor at different time points).

Therefore, to determine $hcond$, Obtain $M(t)$ through experiment and subsequent data fitting. MeasureA_0, Ta, Ts as described above. Utilize the provided equation with the obtained values to calculate h_{cond} at various time points.

4.3. Mass Transfer Coefficient (K_m)

The information provided does not explicitly mention *Km***.** However, the equation

$$N_{sh} * A_0 = \frac{m_{cond}}{PM_{H20}} \quad (8)$$

Suggests a connection between the MT rate ($N_{sh}A_0$) of water vapor from the air to the surface and the condensate flow rate (m_{cond}).

m_{cond} (Molar rate of condensation): This represents the rate at which water vapor condenses on the bottle surface in moles per unit time (mol/s).

PM_{H20} (Molar mass of water): This is a constant value representing the mass of one mole of water (18.015 kg/mol).

$N_{sh} * A_0$ (Mass transfer rate): This represents the rate at which water vapor molecules transfer from the bulk air (A_0) to the bottle surface in kg/s.

$$N_{sh} = K_m * A_0 * (Ca - Cs) = \frac{m_{cond}}{A_0 * (PM_{H20})} \quad (9)$$

K_m might be involved in a separate equation relating to other parameters, such as the air-water vapor concentration difference, diffusion coefficient, and properties of the boundary layer near the bottle surface.

Concentration of Water Vapor in Ambient Air (kg/m³) or (mol/m³)

$$Ca = RH * \frac{PA_{Sat}}{RTa} \quad (10)$$

Where, RH = relative humidity (e.g., 0.6 for 60%). PA_{Sat} = saturation vapor pressure at the ambient temperature. Ta = ambient temperature (K)

Concentration of Water Vapor on the Bottle Surface (kg/m³) or (mol/m³)

$$Cs = \frac{P_{Sat}}{RT_s} \quad (11)$$

Where: P_{Sat} = saturation vapor pressure at the surface temperature.

R = universal gas constant (8.314 J/ (mol·K))

T_S= surface temperature (K)

Additional Information

- The Clausius- Clapeyron equation or standard reference tables based on temperature can be used to determine the saturation vapor pressure.
- Relative Humidity (RH) is defined as the proportion of the water vapor's partial pressure to the saturation vapor pressure at a given temperature [21][22].
- We know the temperatures of the surface, the ambient air, and the relative humidity and use these formulas to calculate the concentrations.

Antoine's equation for estimating the Water saturation vapor pressure. It is given by:

$$Log_{10}P_{Sat} = X - Y/ (Z+T) \quad (12)$$

Where:
P_{Sat} = saturation vapor pressure (mmHg),
Water Constants: X: 8.07131, Y: 1730.63, Z: 233.426;
X, Y, Z= Antoine constants for water. T = temperature (°C)

5. Steps to Calculate Heat Transfer in SCB Bottle Warming

Calculate Saturation Vapor Pressure, then Use in Concentration Formulas: Convert P_{Sat} from mmHg to Pa (1 mmHg = 133.322 Pa). Apply the vapor pressure in the concentration formulas:

$$\text{Surface:} \quad Cs = \frac{P_{Sat}}{RTs} \quad (13)$$

and

$$\text{Ambient:} \quad Ca = RH * \frac{P_{Sat}}{RTa} \quad (14)$$

Relative Humidity RH = 0.60. Calculate P_{Sat} for each temperature: Use the given constants in Antoine's equation. Convert to Pa. Calculate concentrations using the formulas above.

The empirical equation for the heat transferred by convection,

$$q\ conv = C_{conv} * (Ta - Ts)^n \quad (15)$$

Where: C_{conv} = empirical constant (Assume in the paper, C_{conv}: 0.026 W/m^2·K).$n = 2$.Ta = ambient temperature, 30°C.Ts = surface temperature, 25°C.This quadratic relationship shows that the heat transfer increases with the square of the temperature difference between the ambient air and the bottle surface.

Calculation Steps: Determine the temperatures Ta and Ts . Apply the equation using the given constant $Cconv$

Calculate $q\ conv = 0.026 * (30 - 25)^2$

Contribution to Total Heat: $q\ conv$ use it along with $q\ cond$ and $q\ rad$ to calculate $q\ total$.

Contribution Calculation:

$$q\ total = q\ conv + q\ cond + q\ rad \quad (16)$$

Percent Contribution,

$$q\ cond\ \% = \frac{q\ cond}{q\ total} * 100 \quad (17)$$

Key Findings

Higher Contribution – $q\ cond$: Indicates that condensation significantly affects the warming process, possibly due to latent heat release.

Comparison: $q\ cond$ often exceeds $q\ conv$ in contribution, emphasizing the importance of considering condensation in thermal models.

Table 2. Heat Rates for SCB Bottle Warming RH 48%, Temp 22 Deg C

Time	q_{cond}	q_{conv}	q_{total}	$q_{cond(\%)}$	Time	q_{cond}	q_{conv}	q_{total}	$q_{cond(\%)}$
s	J/s	J/s	J/s	%	s	J/s	J/s	J/s	%
0	7.187	0.016	7.203	99.78	360	5.941	0.001	5.942	99.99
30	7.091	0.014	7.105	99.80	420	5.748	0.002	5.750	99.96
60	6.995	0.013	7.007	99.82	480	5.558	0.004	5.562	99.92
90	6.900	0.012	6.912	99.83	540	5.365	0.006	5.371	99.89
120	6.804	0.010	6.814	99.85	600	5.174	0.008	5.182	99.85
150	6.708	0.009	6.716	99.87	660	4.981	0.009	4.991	99.81
180	6.611	0.007	6.618	99.89	720	4.791	0.011	4.802	99.77
210	6.517	0.006	6.523	99.91	780	4.598	0.012	4.610	99.73
240	6.420	0.004	6.425	99.93	840	4.407	0.013	4.421	99.70
270	6.324	0.003	6.327	99.95	900	4.215	0.014	4.229	99.66
300	6.133	0.002	6.135	99.97					

5.1. Condensation Heat (q_{cond})

Starts high and gradually decreases over time. Initially, it contributes nearly all of the total heat transfer. Total Heat (q_{total}): Includes condensation, convection, and possibly radiation contributions. Decreases slightly over time, consistent with the decrease in q_{cond}. Percent Contribution of Condensation Heat: Ranges from 99.78% to 99.66% over 15 minutes. This indicates that condensation is the dominant heat transfer mechanism, contributing to almost all of the heat gained by the bottle.

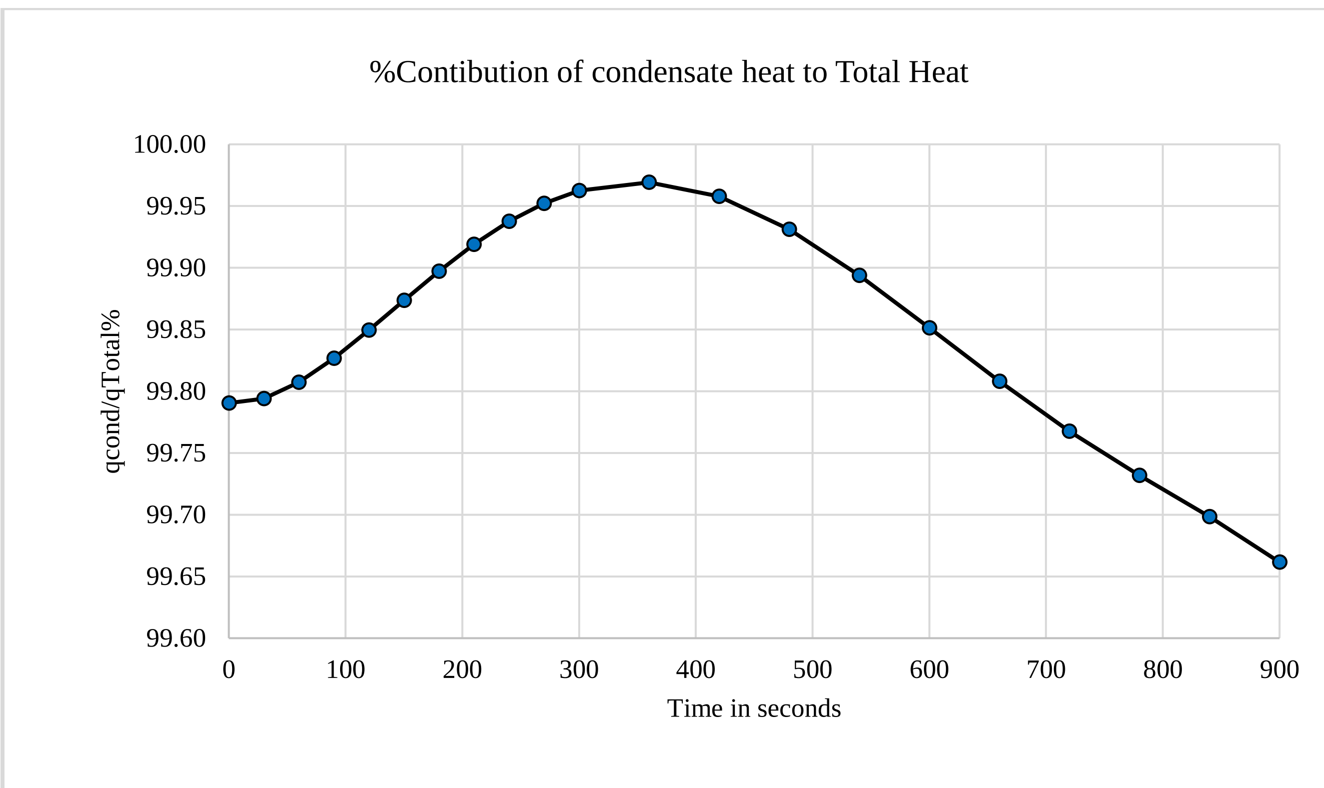

Fig. 4 % contribution of condensate heat to total heat

$$\%Contribution = 99.7903 - 0.641 * 10^{-4}t + 0.7138 * 10^{-5}\, t^2 - 2.3812 * 10^{-8}t^3 + 2.6805 * 10^{-11}t^4 - 1.0298 * 10^{-14} * t^5 \quad (18)$$

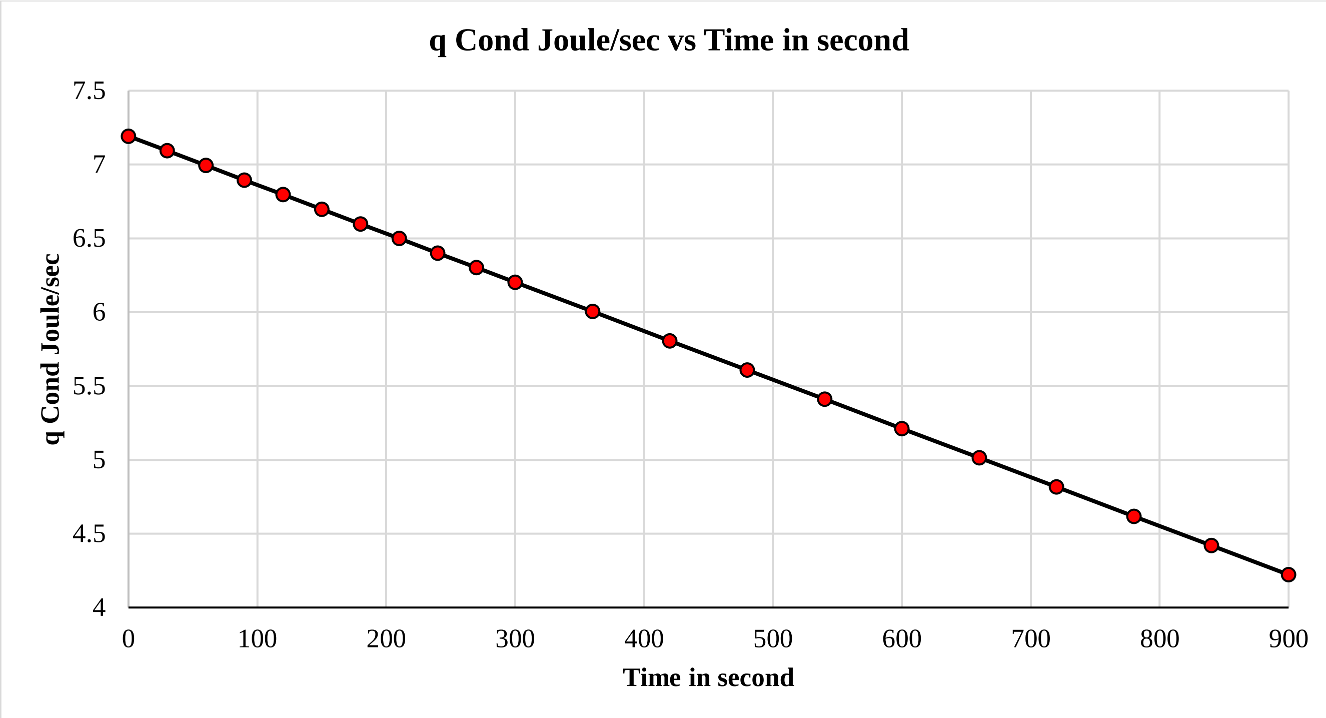

Fig. 5 % contribution of condensate heat to total heat

$$qCond = 7.19226 - 0.00334\ t \quad (19)$$

5.2. Key Observations

5.2.1. Dominance of Condensation

$qCond$ remains the primary contributor to $qTotal$ total throughout the warming process. The high percentage underscores condensation's significant role in the bottle's thermal dynamics.

5.2.2. Gradual Decrease

Both q_{Cond} and $q_{\ Total}$ decrease over time, likely due to diminishing temperature gradients as the bottle equilibrates with the ambient temperature.

5.2.3. Implications: Thermal Management

Understanding the dominant role of condensation can inform better thermal management strategies in similar scenarios, such as optimizing bottle design or storage conditions**.**

5.3. Summary

Determining h_{cond} requires experimental data for M(t), measurement of A_o, Ta, and Ts(t), and knowledge of the latent heat of vaporization (ΔH). K_m is not directly obtainable from the given information but might be related to the mass transfer rate through an additional equation. If you have further information about the specific experiment or the equations used to relate NaAo to other parameters, it might be able to offer more insights into K_m.

6. Conclusion

This study demonstrates that HT via condensation dominates the rate of warming of the Sweetened Carbonated Beverage bottle during the first 900 seconds. The temperature and the accumulated condensate mass exhibit a quadratic dependence on time, indicating a rapid initial rise. While relative humidity plays a role, the impact of ambient temperature on the mass transfer coefficient ($h_{\ cond}$) is more significant within the investigated conditions. Furthermore, hcond exhibits a positive correlation with relative humidity, implying enhanced condensation at higher humidity levels. Conversely, $h_{\ cond}$ exhibits a negative correlation with ambient temperature, suggesting decreased condensation efficiency at higher temperatures.

Future Research Directions

This study provides valuable insights into the coupled HMT mechanisms driving the warming of Sweetened Carbonated Beverages (SCBs). However, several avenues for future research remain unexplored and offer opportunities for further advancements in this field: Optimization of bottle design, Enhanced modelling and simulation techniques, Experimental studies on alternative beverage types and Environmental Factors, and Integration of sustainability in packaging solutions.

By addressing these research directions, future studies can significantly enhance the thermal management of SCBs, paving the way for innovative packaging solutions that ensure better temperature control, improved consumer satisfaction, and sustainability in beverage packaging. These efforts will also contribute to broader applications in thermal management across other consumer products.

Nomenclature

A_0 (m^2)	SCB or CSD PET bottle External Area
C_{conv}	Empirical constant (Assume, C_{conv}: 0.026 W/m^2·K)
Ca	Concentration of W.V. in the air or ambient (kg/m³ or mol m-3) or $C_{A\infty}$
Cs	Concentration of W.V.at the bottle surface (typically assumed to be zero due to condensation) or C_{AP} in ((kg/m³ or mol m^{-3})
h_{conv}	Natural convection HT coefficient (W m^{-2} K^{-1})
h_{cond}	Condensation HT coefficient (W m^{-2} K^{-1})
k	Thermal conductivity of the air,
K_m	Mass transfer coefficient (m s^{-1})
L	Characteristic length of the bottle (e.g., diameter),
M	Mass of Condensed water (kg) or $M(t)$
m_{cond}	Rate of Condensate mass flow (kg s^{-1})
N_A	Molar flux Water (mol s^{-1} m^{-2})
N_{Sh}	Sherwood number (dimensionless)
N_{Nu}	Nusselt number (dimensionless)
N_{Pr}	Prandtl number
P_{Sat}	Water saturation pressure (N m^{-2})
P_{ASat}	Saturation vapor pressure at the ambient temperature.
PM_{H2O}	Water molecular weight (kg mol^{-1}) or molar mass of water
Q	Rate of HT (J s^{-1} or Watts).
q_{Total}	Rate of Total H.T.(J s^{-1})
q_{Cond}	Rate of Condensation H.T.(J s^{-1})
$q_{\ conv}$	Rate of Natural convection HT (J s^{-1})
$q_{\ rad}$	Rate of Radiation HT (J s^{-1})
R	Universal gas constant (8.314 J/(mol·K))
RH	Air Relative humidity (dimensionless) (e.g., 0.6 for 60%)
Ts	Bottle surface temperature (°C).
Ta	Ambient temperature (°C).
$\triangle H_{cond}$	Condensation enthalpy (J kg^{-1})
X	Antoine equation constant **X**: 8.07131 for Water
Y, Z	Antoine equation constants, **Y**: 1730.63, **Z**: 233.426 for Water
HT	Heat Transfer
MT	Mass Transfer
RH	Relative humidity
HMT	Heat and Mass Transfer

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