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How Beverages Cool: Studying Heat Transfer through Concentration, Convection, and Container Material

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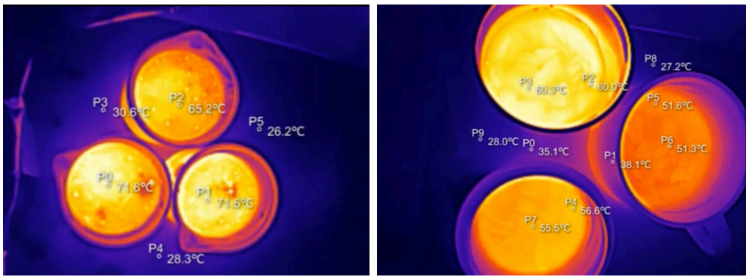
Graphical Abstract



Abstract

This study investigated how concentration, stirring, container material, sugar content, particle loading and volume affect the cooling of common everyday stables Coffee, tea and oat mix suspensions were used to model fluids. Temperature changes were recorded using an InfiRay thermal camera over 180–420 seconds. Coffee trials showed that increased solute concentration reduced the cooling rate due to higher viscosity, damping natural convection. Stirring accelerated cooling, promoting forced convection and increasing the convective heat transfer coefficient. Tea experiments demonstrated that sugar addition and container material significantly altered cooling behaviour, with insulated metal cups retaining heat most effectively. The milo-oat trials showed that with increasing particle concentration, mixing within the fluid improves, leading to faster cooling. Smaller water volumes also cooled more quickly because they had lower thermal inertia, as well as, a greater surface-area-to-volume ratio. These findings were consistent with Fourier's Law of Conduction and Newton's Law of Cooling, demonstrating how these theories apply in practical situations. Furthermore, highlighting practical insights into the design of beverage containers, ready-to-drink formulations and broader applications in thermal management and food engineering. The use of experimental data along with thermal pictures and theory models is a great method for understanding how to control moving heat around hands-on situations efficiently.

Keywords: heat transfer, conduction, convection, beverage cooling, solute concentration, stirring, thermal imaging.

1. Introduction

From energy systems to food processing and consumer product design, efficient thermal management is a fundamental concern in various engineering disciplines. The rate at which heat is transferred from a hot substance to its surrounding environment determines the performance, safety and user experience of many such applications. The core of thermal energy engineering lies in the principles of conduction, convection and radiation, all of which are governed by physical laws such as Fourier's Law of heat conduction and Newton's Law of cooling. Although these two laws have been well established in the theoretical context, their application in real life and complex chemical systems is still an ongoing study.

Especially in the field of food and beverage systems, this provides a powerful analytical platform for studying convective and conductive heat transfer under nonideal conditions. Unlike pure liquids, beverages typically contain dissolved solids, such as sugar, or suspended particles, such as oats and grains, which can significantly alter the internal fluid dynamics and thermal behaviour. These constituent factors can affect viscosity, density gradient, boundary layer development and natural or forced convection. All of these factors can accelerate or slow down the efficiency of heat dissipation. In addition, the material properties of the containers for holding fluids, including their thermal conductivity, heat capacity and insulation, play a role in determining the rate of temperature loss. These elements reflect the engineering challenges faced in the design of industrial heat exchangers, slurry reactors and thermal packaging solutions.

Although the cooling of beverages is a simple and easily understandable phenomenon, it involves complex thermodynamic interactions. Previous studies have explored convection patterns and cooling rates under controlled laboratory conditions, but few have combined thermal imaging techniques with experiments involving the comparability and variable control of solute, particle and container effects. Furthermore, daily behaviours like stirring are a method to induce the formation of convection, which can be linked to macroscopic changes in heat transfer.

This research aims to systematically explore the influence of various physical and component variables on the cooling behaviour of common hot beverages, thereby filling the research gap in the field. We used the InfiRay thermal image for real time temperature tracking and analysed the temperature change curves of coffee, tea and oat liquid under different conditions. In other words, we investigated the effects of factors such as solute concentration, amount of sugar added, liquid volume, stirring or unstirring and material of containers on heat loss over time. Among them, stirring is used to simulate forced convection and changes in concentration and particle load help us understand how fluid composition regulates natural convection. The container materials are glass, ceramics and insulating metals respectively, their thermal conductivity and heat preservation performance are all within the scope of research.

By combining experimental data with theoretical heat transfer models, this research builds a bridge between principle and reality. The research results not only verified the key thermodynamics laws, but also proposed some feasible strategies that can be used in the design of beverage formulas, the improvement of packaging and optimisation of thermal equipment to enhance or delay the cooling process. Furthermore, the research also indicated that thermophysical experimental models based on the food system have potential value in industrial applications. This research provides a useful reference for extensive discussions on material selection, fluid behaviour and process optimisation in thermal engineering.

2. Materials and Methods

2.1 Experiment Setup

All experiments were conducted at an ambient laboratory temperature of 22 °C. An InfiRay thermal camera recorded fluid temperatures at 30–60 second intervals; each reported value represents the average of five independent measurements. For every trial, readings were taken at the geometric centre of the fluid. In some of the other experiments, additional measurements were made at the inside edge of the vessel wall.

2.2 Coffee Cooling Trail

2.2.1 Effect of Solute Concentration

75 mL of water was added to each of three beakers and heated to approximately 70 °C. Three different types of coffee were then added to the respective beakers. A thermal camera was used to observe the temperature changes. The initial temperature of the coffee in each beaker and the temperature surrounding the beaker were recorded. The coffee and surrounding temperatures were recorded at 60-second intervals (0 to 480 seconds). Subsequently, three new 100 mL beakers were prepared, each containing 4 g of the respective coffee types and 75 mL of water, which were again heated to approximately 70 °C. Initial temperatures were recorded, followed by temperature measurements at 60-second intervals for a total of 480 seconds. The same procedure was applied to samples containing 2 g of solute in 75 mL water to evaluate the effect of reduced concentration on cooling behaviour.

2.2.1 Effect of Stirring (Forced Convection)

75 mL of water was added to each of three beakers and heated to approximately 70 °C. Then, 4 g of three different types of coffee were added to the respective beakers. Over a period of 480 seconds, the temperature of the coffee and the surrounding environment was measured at 60-second intervals using a thermal camera. During this time, the coffee was stirred at a constant rate to simulate forced convection, in order to investigate whether enhanced convection accelerates the cooling rate. The results were compared to those from a previous step in which 4 g of coffee was added without stirring, to evaluate the effect of enhanced convection under identical solute concentration.

2.3 Container Material Comparison

2.3.1 Coffee Trail - Cup Material Comparison

100 mL of water and 2 g of the same type of coffee were added to a glass cup, a metal insulated cup, and a ceramic cup. A thermal camera was used to record the temperature over 480 seconds to evaluate the effect of different container materials on the cooling rate.

2.3.2 Tea Trail - Cup Material Comparison

To assess container-material effects without added sugar, two teabags of Twinings Camomile & Spiced Apple (4 g total) were steeped in 200 mL boiling water for 4 minutes. The infusion was then poured into a ceramic mug, a stainless-steel insulated mug and a glass beaker. Following a single stir, centre temperatures were logged every 30 seconds for 240 seconds.

2.4 Solute Addition Effects

For this trial, 5 g of sucrose was dissolved in 200 mL boiling water, then two teabags were steeped for 4 minutes. After removing the bags and stirring once, centre temperatures were recorded every 30 seconds over 240 seconds.

2.5 Particle-Induced Convection and Volume Effects

2.5.1 Effect of Oat Concentration

To determine the effect of particulate loading on cooling, milo-oat suspensions were prepared by dispersing 0.5, 1 and 2 packets of oats (17.5 g, 35 g and 70 g, respectively) into 200 mL of deionised water. After a single gentle stir to homogenise, samples were allowed to cool uncovered. Centre temperatures were logged every 30 seconds from 0 to 180 seconds.

2.5.2 Effect of Fluid Volume

The influence of fluid volume was examined by suspending one packet of oats (35 g) in 100 mL, 150 mL and 200 mL of water. For the 200 mL trial, both centre and near-wall temperatures were recorded; for the 100 mL and 150 mL trials, only centre readings were taken. All measurements were logged every 30 seconds for 180 seconds.

3. Results

3.1 Coffee Cooling Trail

3.2.1 Effect of Solute Concentration

A comparison of the cooling rates of unstirred coffee samples with identical concentrations revealed differences among the three coffee flavours (caramel latte, cappuccino and latte). According to the data in Tables 1 and 2, the caramel latte flavour exhibited a faster cooling rate than the other two types at both concentration levels. When comparing the temperature drops of the same coffee type over 480 seconds at 2 g and 4 g concentrations, the 2 g caramel latte sample cooled by 16 °C, whereas the 4 g sample cooled by only 11.7 °C over the same time. This trend was consistent across all three coffee flavours.

Table 1 – Temperature change of 2 g of three different coffee flavours in 75 mL of water for 480 seconds without stirring.

Time (sec)	Caramel Latte (℃)	Cappuccino (℃)	Latte (℃)	Surrounding temperature (℃)		
				Caramel Latte/CL(℃)	Cappuccino/C (℃)	Latte/L (℃)
0	73.1	69.6	71.5	29.3	26.3	28.8
60	70.5	66	69.2	30.7	26.5	28.5
120	68.7	64.5	67.8	31.3	25.9	28
180	66.8	62.2	65.9	32.3	26.7	28.7
240	64.6	61.9	63.8	32.2	26.5	28.8
300	62.9	59.1	63	32.3	26.3	28.7

360	60.7	57.5	61.9	32.7	26.5	28.8
420	58.7	56.4	59.8	32.9	26.8	29.1
480	57.1	56	58.3	32.5	26.4	28.6

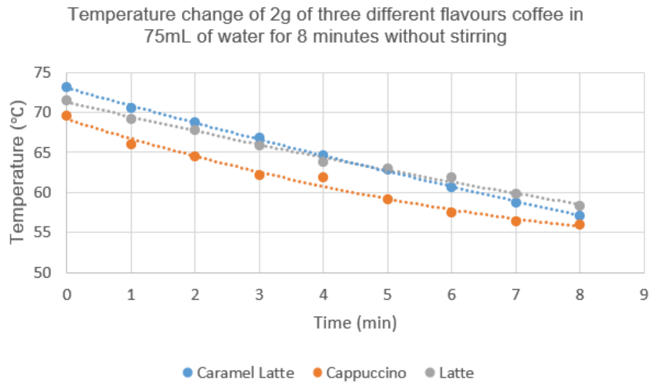


Figure 1 - Cooling Trend of 3 different flavours of coffee (2g) without stirring.

Table 2 - Temperature change of 4 g of three different coffee flavours in 75 mL of water for 480 seconds without stirring.

Time (sec)	Caramel Latte (℃)	Cappuccino (℃)	Latte (℃)	Surrounding temperature (℃)		
				CL(℃)	C(℃)	L(℃)
0	75.9	73.2	76.6	31	30	31.4
60	74.5	71.5	75.5	31.4	30.3	32
120	73.1	70.3	74.1	32.6	30.3	32.1
180	72	68.5	72	33.2	31.8	32.5
240	70.5	67.2	70.8	32.7	32.2	32.2
300	68.9	66.5	69.7	31.5	31.6	31.7
360	67.5	64.2	68.3	31	30.4	32.3
420	65.2	62.8	67	30.8	29.7	32.1
480	64.2	62	65.3	31.2	30.1	31.6

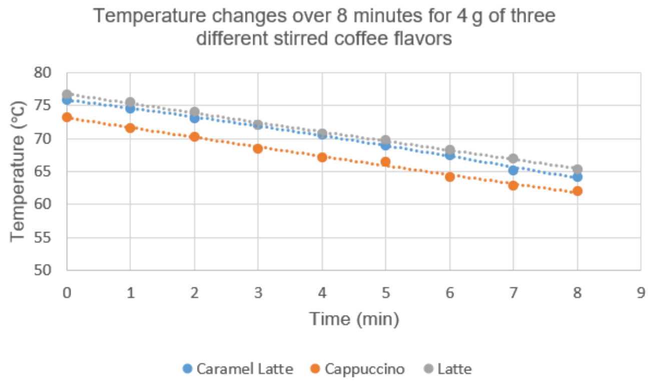


Figure 2 - Cooling trend of 3 different flavours of coffee (4g) without stirring.

2.2.1 Effect of Stirring (Forced Convection)

When the coffee samples had the same concentration (4 g of solute), under stirred conditions, the fluid cooled faster than unstirred conditions. All three coffee flavours showed a bigger temperature drop under stirring conditions.

Table 3 - Temperature changes over 480 seconds for 4 g of three different stirred coffee flavours in 75 mL of water.

Time (sec)	Caramel Latte (℃)	Cappuccino (℃)	Latte (℃)	Surrounding temperature (℃)		
				CL(℃)	C(℃)	L(℃)
0	77.2	68.9	76.4	32.8	33.2	32.7
60	76.7	66.5	75.5	33.2	33.5	33
120	72.7	64.2	73.3	34.9	33.6	33.2
180	70.9	62.5	71.1	35.3	33	33.4
240	67.1	61.7	68	36.7	33.8	34.3

300	66.3	60.2	66.2	36.7	33	33.4
360	64.5	58.7	64.9	36.9	34	34.2
420	63.7	57	63.2	35.6	32.3	32.7
480	60	56.2	62.7	36.9	33	33.6

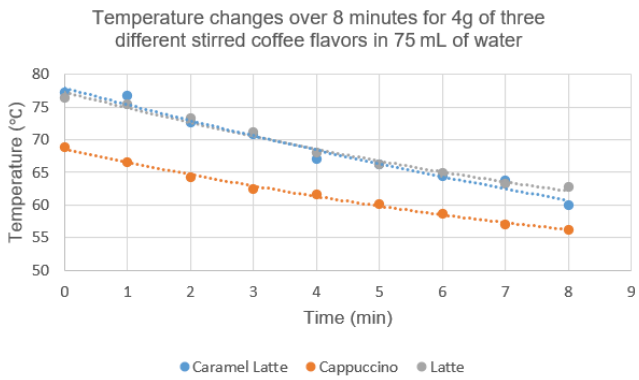


Figure 3 - Cooling trends of 3 types of coffee (4g each) dissolved in water and stirred.

3.2 Container Material Comparison

3.2.1 Coffee Trail - Cup Material Comparison

Coffee of the same flavour and concentration showed noticeable variations in temperature change over 480 seconds when placed in the three different containers. The metal insulated cup retained the most heat, while the glass cup showed the greatest temperature decrease.

Table 4 - Temperature changes over 480 seconds for coffee of the same flavour and concentration in different containers.

Time (sec)	Glass cup(℃)	metal insulated cup (℃)	ceramic cup(℃)	Surrounding temperature (℃)		
				Glass cup(℃)	metal insulated cup (℃)	ceramic cup(℃)
0	64.7	69.8	63.5	28.5	39.7	38.4
60	63.7	68.7	61.4	38.9	38.9	39.1
120	63	67.2	60.4	38.6	38.6	40.1
180	61.6	66.1	58.4	37.1	37.1	39.7
240	60.8	64.3	57.8	37	37	39.3
300	58.3	62.2	55.6	36.7	36.7	39.5
360	57.4	62.2	53.7	35.9	35.9	38.5
420	56.4	61.4	53.2	35.3	35.3	38.4
480	54.6	60.1	52	35.1	35.1	38.1

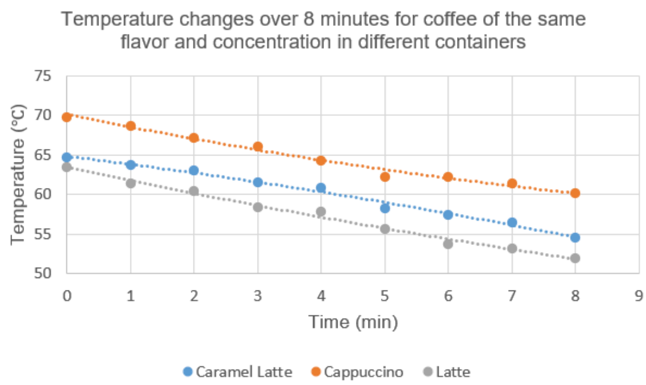


Figure 4 - Cooling trend for coffee of the same flavour and concentration in 3 different containers.

3.2.2 Tea Trail - Cup Material Comparison

Container material exerted a strong control on tea cooling. Over 240 seconds, a porcelain mug retained heat best (ΔT = 6.8 °C), glass was intermediate (8.6 °C) and stainless steel cooled fastest (12.4 °C).

Table 5 - Temperature changes over 240 seconds for tea of the same flavour and concentration in different containers.

Time (sec)	Ceramic (°C)	Stainless-Steel (°C)	Glass (°C)
0	72.7	68.1	70.1
60	70.1	61	65.7
120	68.3	59.1	64.1
180	67.9	58	63
240	65.9	55.7	61.5
ΔT	6.8	12.4	8.6

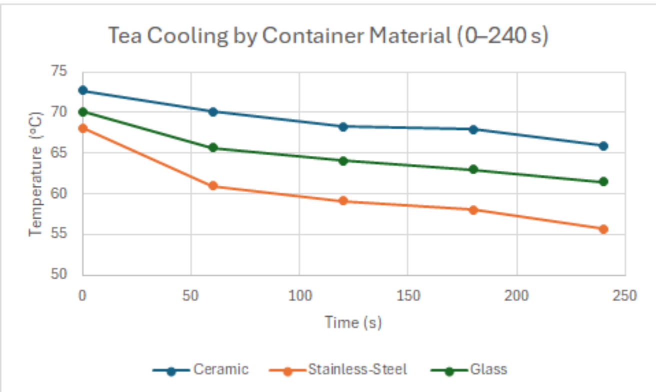


Figure 5- Cooling trend for tea of the same flavour and concentration in 3 different containers.

3.3 Solute Addition Effects

Dissolving 5 g sucrose before steeping two teabags resulted in a greater 240 s ΔT (10.3 °C) than the unsweetened infusion (8.6 °C).

Table 6 - Temperature change of tea samples with and without sucrose over 240 seconds.

Time (sec)	No Sucrose (°C)	+ 5 g Sucrose (°C)
0	70.1	68.1
30	68.4	66.7
60	65.7	64.3
90	64.9	62.9
120	64.1	61.9
150	63.4	60.7
180	63	59.8
210	62.3	58.9
240	61.5	57.8
ΔT	8.6	10.3

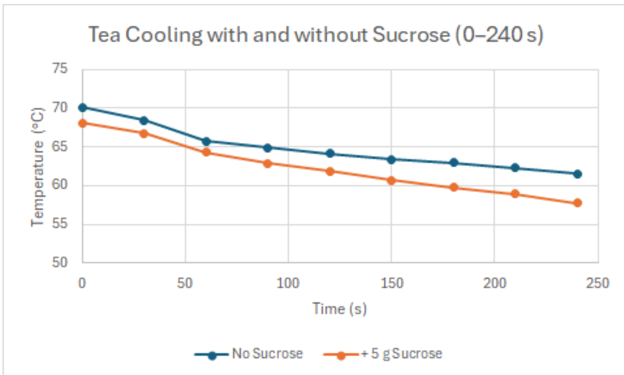


Figure 6- Cooling trend for tea samples with and without sucrose over 240 seconds.

3.4 Particle-Induced Convection and Volume Effects

3.4.1 Effect of Oat Concentration

Increasing the milo-oat concentration from 0.5 to 2 packets in a fixed 200 mL volume resulted in the 2-pack suspension losing 24.0 °C, compared with just 16.0 °C for the 0.5-pack sample over 180 seconds.

Table 7 - Temperature change of milo-oat suspensions with different oat concentrations over 180 seconds.

Time (sec)	100 mL Centre (°C)	100 mL Edge (°C)	150 mL Centre (°C)	150 mL Edge (°C)	200 mL Centre (°C)	200 mL Edge (°C)
0	71.2	69.7	67.2	65.7	67.2	65.7

30	61	59.5	64.9	63.4	65.1	63.6
60	50.7	49.2	59.3	57.8	64.3	62.8
90	49.3	47.8	57.8	56.3	63.9	62.4
120	47.9	46.4	57.3	55.8	62.2	60.7
150	47.2	45.7	55.7	54.2	61.3	59.8
180	46.5	45.1	54.2	52.6	59.3	57.7
ΔT	24.7	24.6	13	13.1	7.9	8

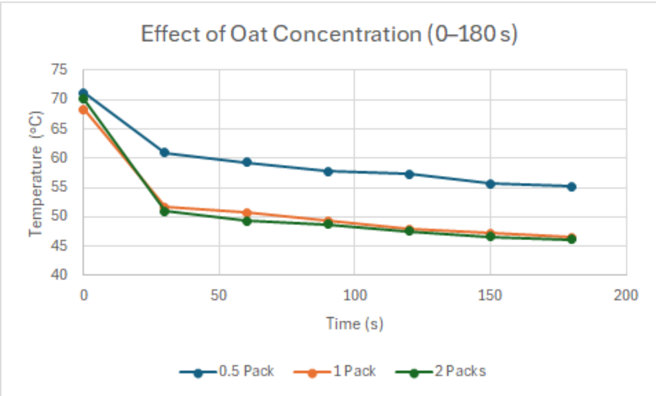


Figure 7 - Cooling trend for milo-oat suspensions at varying oat concentrations over 180 seconds.

3.4.2 Effect of Fluid Volume

Holding oat mass constant but reducing water volume caused the 100 mL suspension losing 24.7 °C at the centre (24.6 °C at the edge), whereas the 150 mL sample lost 13.0 °C (13.1 °C at the edge) and the 200 mL beaker lost only 7.9 °C at the centre (8.0 °C at the edge).

Table 8 - Temperature change of milo-oat suspensions at different fluid volumes over 180 seconds.

Time (sec)	0.5 Pack (°C)	1 Pack (°C)	2 Packs (°C)
0	71.2	68.4	70.1
30	61	51.7	51
60	59.3	50.7	49.3
90	57.8	49.3	48.7
120	57.3	47.9	47.6
150	55.7	47.2	46.6
180	55.2	46.5	46.1
ΔT	16	21.9	24

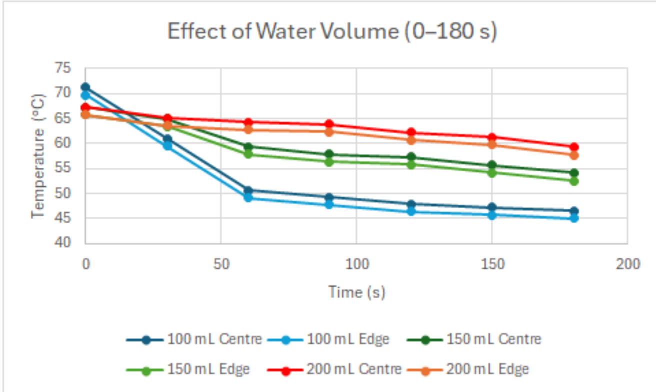


Figure 8 - Cooling trend for milo-oat suspensions at different fluid volumes over 180 seconds.

4. Discussion (need to be edited)

The experiments showed that several factors affected how fast the beverages cooled. For the coffee samples, changing the solute concentration made a noticeable difference. Tables 1 and 2 and Figures 1 and 2 showed that when the concentration increased from 2 g to 4 g, the drinks cooled more slowly. For example, in the caramel latte the 2 g sample cooled by 16 °C over 480 seconds, while the 4 g sample cooled by only 11.7 °C. This indicates that having more dissolved solids seemed to increase the viscosity of the coffee, which most likely slowed down the natural convection flow that usually helps carry heat. A similar trend was seen in the tea trial. Table 6 and Figure 6 showed that adding 5 g of sugar caused a larger temperature drop (ΔT = 10.3 °C) compared to tea without sugar (ΔT = 8.6 °C).

Stirring also had a big impact on how quickly the coffee cooled. When stirring was introduced, the cooling rate increased for all three coffee flavours. Table 3 and Figure 3 showed that caramel latte cooled by 17.2 °C under stirring conditions, compared to 11.7 °C without stirring. Stirring created forced convection, which moved the liquid around and improved heat transfer. Faster fluid flow likely increased the convective heat transfer coefficient. As a result, the Nusselt number would have increased ($Nu = h * L / k$), which explains why the heat left the drink more quickly.

The type of cup also made a difference. In the coffee and tea tests, the metal insulated cup and the ceramic mug kept the drinks warmer for longer, while glass allowed them to cool faster. Table 4 and Figure 4 showed that coffee in the insulated metal cup only cooled by 9.7 °C over 480 seconds, while coffee in a glass cup cooled by 11.5 °C. To support that, in the tea trials (Table 5 and Figure 5) similar results were seen. The ceramic cup had the smallest temperature drop (6.8 °C), while the stainless steel cup cooled the fastest (12.4 °C). The insulated and ceramic cups seemed to slow down heat loss by reducing conduction through the walls. The glass cup probably allowed faster heat transfer to the air outside.

The milo-oat experiments showed that adding more oat particles made the drink cool faster. Table 7 and Figure 7 showed that the 2-pack suspension lost 24 °C over 180 seconds, while the 0.5-pack sample lost only 16 °C. The extra particles probably encouraged more movement in the fluid, which increased natural convection inside the drink and helped the heat move from the centre to the outside.

Finally, the water volume experiments (Table 8 and Figure 8) confirmed that smaller volumes cooled faster due to lower thermal inertia and a larger surface-area-to-volume ratio. The 100 mL oat suspension cooled by 24.7 °C, while the 200 mL sample cooled by only 7.9 °C at the centre. The small temperature difference between the centre and edge (≤ 0.2 °C) also showed that conduction within the liquid was not a limiting factor for heat transfer in these cases, meaning that convection remained the main way heat moved through the fluid.

Overall, the experimental results support Fourier’s Law of Conduction and Newton’s Law of Cooling. Firstly, Fourier's Law helped explain how the container materials affected the rate of heat transfer by conduction through the walls. While on the other hand, Newton’s Law described the convective cooling from the liquid to the surrounding air. The study showed how thermophysical properties, fluid dynamics, and material conductivity influence cooling rates. These findings have practical applications for consumers and for designing beverage containers, packaging, and thermal equipment.

This study also serves as a learning point for audiences who want to manage how fast their drinks cool. For example, stirring drinks or using glass containers can speed up cooling, while using insulated or ceramic cups can keep drinks warmer for longer. The results could also be helpful for people designing drink containers and packaging. Knowing how to control cooling can also be useful in factories where food and drink products that contain dissolved solids or particles need to be heated or cooled. Changing things like stirring, concentration, and container type could help manage heat transfer in both homes and industry.

5. Conclusion

Overall, the experimental results of this study indicate that the physical composition of beverages and the characteristics of containers have a significant impact on the cooling rate. After analysis, it was found that dissolved solutes with higher concentrations, such as coffee solids, slow down the cooling process by increasing viscosity and reducing convection, while suspended particles like oats enhance convective mixing and accelerate cooling. Stirring promotes forced convection, causing the temperature to drop more rapidly. The material of the container regulates the conduction of heat loss. The insulated metal cup effectively retains heat, while the glass cup helps the drink cool down more quickly.

Smaller liquid volumes cooled faster because they had less thermal inertia and a larger surface-area-to-volume ratio. These results showed how convection and conduction worked together to control how fast heat was lost. The findings can help people choose containers and ingredients to change how fast their drinks cool. They might also be useful for designing food products and industrial systems where controlling heat transfer is important. Subsequent research may include exploring other variables, such as environmental air flow or shape and size of container, to refine these analyses.

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