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Thermal behavior of reusable ice cubes: cooling efficiency and performance analysis

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Abstract

Reusable ice cubes as mini-ice packs have been widely used in the food industry and have played important roles in preventing waterborne diseases and microplastic contamination from using water ice cubes due to unhygienic water sources. This study investigates the thermal performance of various commercially available reusable ice cubes, assessing their cooling efficiency using a DS18B20 thermocouple sensor integrated with an Arduino microcontroller and a HIKMICRO B20 infrared camera. The primary objective is to evaluate and compare the cooling capabilities of different reusable ice cubes by measuring minimum temperatures and cooling times when placed in a water-filled glass. Experimental results indicate that stainless steel ice cubes exhibit faster 2/3 cooling rates due to their higher thermal conductivity, whereas plastic ice cubes achieve lower minimum temperatures. The study further examines the influence of key parameters, including the number of ice cubes (N), water volume (V), and glass diameter (D). Empirical relationships for local plastic ice cubes were derived, showing dependencies of minimum temperature at $T_{\min} \sim N^{1/5} V^{5/3} D^{5/2}$ and minimum cooling at $t_{\min} \sim N^{1/5} V^{1/5} D^3$. These findings provide insights into the usage of reusable ice cube performance for various cooling applications.

Keywords:

DS18B20, ice cubes, reusable, Arduino, thermal imaging

1. Introduction

Ice packs have been used in hospitals, laboratories, and food industries for transporting chemicals, medicine, or perishable food supplies. Reusable ice cubes are ice packs in smaller forms that are used for cooling food and beverages as an alternative to common water-based ice cubes. The cooling method using common ice cubes has been very popular in café, restaurants, or domestic households as it is simple and easy to make. Ice cubes can be made in small numbers using ice trays placed inside domestic refrigerators or on large scales using specialized ice cube refrigerator machines that are specifically designed for the food industry.

Cooling food and beverages using common ice cubes has some unwanted effects as the melted ice will dilute the food and beverages, thus it will slowly reduce the taste. The most serious drawback of using ice cubes is that they may carry waterborne diseases since they are often made from unhygienic water sources. Izani et al. [1] who studied safety issues at food outlets in Malaysia, took water samples from 30 food outlets that were randomly chosen in Kubang Kerian, Kelantan. They found that the ice cubes from 16 outlets (57%) were contaminated with fecal coliforms. Similar situations were also reported by Francesca et al. [2] who investigated food ice cubes in various types of drinks in Sicily Palermo Province, Italy. They took 60 ice cube samples from home-

level productions, bars, pubs, and plants and they found the evidence of micro fungi yeast and mold contamination. Triggiano et al. [3] reviewed the contamination of ice cubes caused by bacteria, viruses, and fungi. They summarized the results from the selected 14 articles on hygienic and sanitary issues of ice cubes. They concluded that ice cubes may get contaminated by bacteria such as *Escherichia coli*, *coliforms*, *Pseudomonas spp.*, or *Staphylococcus aureus*. They also found studies that detect the presence of fungi such as yeast and molds in ice cubes.

Many efforts have been dedicated to inventing alternative materials that can alleviate the weaknesses of water-based ice cubes. The main idea behind these works is how to create ice cubes that can be reused to save costs in the long run. The most important issue that needs to be addressed is that the alternative ice cubes must not melt and mix with the foods or beverages so that the spread of harmful microorganisms can be prevented. Zou et al. [4] created ice cubes using gelatine hydrogels named “jelly ice cubes” (JICs) to reduce water consumption and food waste due to contamination. They proved JICs' stability and heat-absorbing capability by testing them with repeating freeze-thaw cycles. In their other paper, Zou et al. [5] further performed freeze-thaw cycles and determined the properties of JICs in more detail such as latent heat of fusion, water content, mechanical properties, cooling efficiencies, and hydrogel inner structures. Liu et al. [6] developed sustainable self-sanitizing ice cubes using a food-grade mixture of microporous cellulose sponges (MCS) with photosensitizers. Their ice cubes were also tested and proven to withstand multiple freeze-thaw cycles and compressive stresses.

Reusable ice cubes currently sold in the market take the benefits of using Phase Change Material (PCM) to enhance cooling performance. PCM has been studied quite well and there have been many studies on PCM available in the literature. Ezan et al. [7] studied the effect of incorporating a slab of PCM inside a Vertical Beverage Cooler (BVC) numerically using ANSYS™ FLUENT. They found that the PCM inside the BVC enhances the thermal performance by extending the off-duration of the compressor cooler. The PCM materials that can be used for thermal storage applications such as for reusable ice cubes were summarized and reviewed by Oro et al. [8]. They listed 88 PCM materials, 40 of which are commercially available in the market. Pereira da Cunha and Eames [9] also reviewed a large number of PCM materials that are suitable for heat storage applications, especially at low and medium temperatures. They discuss the enhancement of heat transfer by using the PCM materials listed in their paper. The applications of PCM materials specifically for refrigeration systems were reviewed by Selvnes et al. [10]. They discussed the applications of water, ice, and salt solutions as PCM for refrigeration systems which is very similar to the PCM used in commercial reusable ice cubes that are available in the market. They predicted that the use of ice, water, and salt solutions as PCM will grow in the future due to low cost and affordability.

Recently, reusable stainless steel ice cubes have attracted more attention and they have become more popular. They are available in the market in many variants and prices from the cheapest products to the most expensive ones. Hence, the effectiveness of these types of reusable ice cubes compared to common water ice cubes has raised questions and has attracted researchers to study them. Kumar et al. [11] manufactured stainless steel ice cubes filled with PCM made using a mixture of potable water, distilled water, salt, and sugar. They performed rigorous thermal tests on their reusable ice cubes and found that their ice cubes were as good as common ice cubes and they can be used as alternative ice cubes for various kinds of beverages.

Luthfi et al. [12] designed and manufactured stainless steel ice cubes by cutting a stainless plate without using any PCM in them. They mentioned that having PCM material inside stainless steel ice cubes was necessary as their stainless-steel ice cubes did not perform as well as water ice cubes. In his next research, Luthfi [13]

compared the cooling performance of the in-house ice cubes made from cutting plates from his previous research with the commercial stainless steel ice cubes sold in the market by using Arduino-based temperature measurement with DS18B20™ thermocouple sensors. He found that the in-house ice cube with no PCM could not compete with the commercial ones and having PCM inside stainless steel ice cubes was a must. Luthfi et al. [14] then performed extensive comparisons of commercial stainless steel ice cubes sold in the market to find out whether the price of stainless steel ice cubes influences their thermal performance. They applied thermal imaging using an infrared camera for visualization of temperature distribution and DS18B20 thermocouple sensors controlled by Arduino™ microcontroller for temperature measurement. They found that the price difference of the stainless-steel ice cubes does not contribute to the cooling performance of the ice cubes. The cheapest ice cubes performed even better than the more expensive ones.

Reusable ice cubes sold in the market are not limited to stainless steel only. There are many types of them available for purchase such as plastic, granite, soapstone, or ceramic ice cubes. Fleischer et al. [15] compared the cooling performance of many types of reusable ice cubes using digital temperature measurements. Although the measurements were not too detailed and they were performed for class demonstration purposes only, their temperature measurement showed interesting features.

As the cooling performance of plastic ice cubes has not been studied, this study is expected to contribute to filling the research gap in this field of study. Reusable plastic ice cubes will be studied in more detail using thermal imaging visualization and digital temperature measurements as previously performed by Luthfi et al. [14] in investigating stainless-steel ice cubes.

The final objective of this study is to obtain more accurate and comprehensive cooling performance data for plastic ice cubes. Two types of plastic ice cubes sold in the market at different prices together will be compared. The thermal performance comparison will also be performed on stainless steel ice cubes and water ice cubes to find out how good the thermal performance of plastic ice cubes is when compared to other types of ice cubes.

2. Research Methods

The reusable ice cubes tested and compared in this study were obtained from an online marketplace in Indonesia. The equipment and the method for testing the ice cubes were adapted from the work of Luthfi and his colleagues [13], [14]. Water ice cubes were used as references for all the tests conducted and the temperature measurements were performed using DS18B20 thermocouple sensors controlled using Arduino UNO microcontroller. The development of the cold-water temperature inside the glasses was visualized using a thermal camera. In the following sub-sections, the specifications of the equipment used and the testing procedures will be discussed in more detail.

2.1 Reusable Ice Cube Specimens

There are about three types of reusable ice cubes tested and compared in this study. “Betterlife” plastic ice cubes as shown in Fig. 1(a) were locally made and the cheapest ice cubes tested. They were purchased for IDR 14500 for a pack of 12 ice cubes. The ice cubes shown in Fig. 1(b) were “Echo”, Japanese brand ice cubes which were purchased for IDR 39000 for a pack of 8 ice cubes while the stainless ice cubes as shown in Fig. 1(c) were Leeseeph bought for IDR 40800 for a pack of 6 pieces, which were tested comprehensively by Luthfi et al. [14] before. The size and price comparison for each piece of ice cube is shown in Table 1. As can be seen from the table below, stainless steel ice cubes are still the most expensive ice cubes although Leeseeph was the cheapest stainless steel ice cubes tested by Luthfi et al. [14]. All the ice cubes

tested were identical in size to ensure that the comparison was accurate.

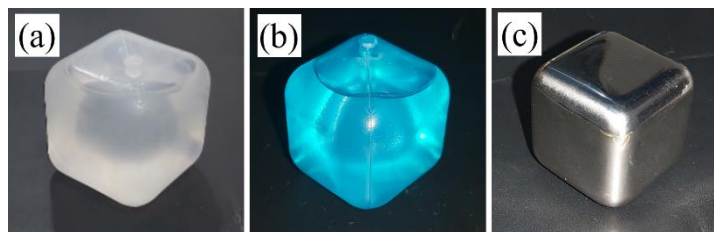


Fig. 1. Reusable ice cubes tested (a) cheap local brand ice plastic cubes, (b) Japanese brand plastic ice cubes, and (c) Leeseeph stainless steel ice cubes.

Most results obtained in this study will be mainly based on the results from local plastic ice cubes. The more expensive Japanese brand ice cubes and the stainless ice cubes were tested for comparison only to find out if the price and the type of reusable ice cubes had an impact on the cooling performance of the ice cubes.

Table 1. Reusable ice cubes comparison

Ice Cube Type	Size	Price
Local brand	25×25×25 mm	IDR 1210/piece
Japanese Brand	25×25×25 mm	IDR 4875/piece
Leeseeph	25×25×25 mm	IDR 6800/piece

Preliminary examination of the reusable ice cubes to be tested revealed that all of the ice cubes had some kind of liquid inside them which was most likely food-grade PCM. No information about the detailed composition of the PCM liquid inside the ice cubes was written on the label of the ice cubes. The type of plastic used for both plastic ice cubes was also not given but it must be food grade and safe to be used for beverages and food preparation.

2.2 Temperature Measurement Setup

In the experiments, the temperature changes of the water inside the glass due to each type of ice cube tested were measured digitally using DS18B20 thermocouple sensors powered by Arduino UNO microcontroller. The Arduino setup for the tests was prepared according to the work of Luthfi and his colleagues [13], [14]. DS18B20 sensors and Arduino have been very popular ways of measuring temperatures for many types of applications and purposes such as health monitoring system [16], automatic dispenser for blind people [17], or stress level detection [18].

Before performing temperature measurements, DS18B20 thermocouple sensors and the Arduino microcontroller were connected to a computer. The general setup of the microcontroller and the sensors is shown in Fig. 2.

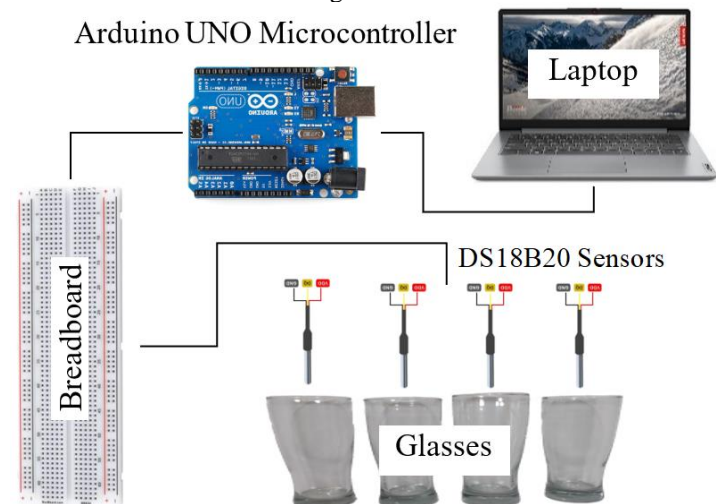


Fig. 2. Temperature measurement setup using DS18B20 sensors with Arduino™ UNO microcontroller.

There were about 5 sensors applied with 4 sensors placed inside each of the 4 glasses and 1 sensor for measuring the surrounding air temperature. All sensors were connected first to an 830-hole breadboard. To ensure secure and firm connections to the breadboard, the sensor wires were first fitted into 5 set 3-pin terminal blocks. Each sensor has 3 types of wire, vcc (red wire), data (yellow wire), and ground (black wire). Each set of wires was connected to the breadboard using 10 cm male-to-male jumper wires. The data wires were powered from VCC wires by connecting them using a 4.7 k Ω resistor. All wires were then connected to the Arduino board using 20 cm male-to-male jumper wires. A 2 \times 16 I2C-LCD was used for displaying the temperature reading. The Arduino board was connected to a laptop computer using a mini-USB to USB type A connector cable. The detailed electronic components used for setting up temperature measurements were adapted from the work of Luthfi et al. [14].

2.3 Thermal imaging

A thermal camera was used to visualize the cold-water development inside the glass due to ice cubes. The equipment applied in this experiment, the HIKMICRO™ B20 thermal camera, was successfully used by Luthfi et al. [14] for visualizing the cold temperature development of water inside glasses filled with stainless-steel ice cubes. The camera has an accuracy of ± 2 °C and ± 2 % at ambient temperatures of 15 °C to 35 °C and object temperatures above 0 °C. The thermal sensitivity of the camera is 40 mK with a temperature range of -20 °C to 550 °C and frame rates of 25 Hz.

The thermal camera which has an infrared sensor resolution of 256 \times 192 pixels was fitted on a tripod and placed around 1.5 m in front of all glasses used in the experiments. The setup of the infrared camera, the tripod, and the glass for taking thermal images during experiments is shown in Fig. 3(a). The default color scheme, *Ironbow*, which shows low temperature in purple color and high temperature in yellow color was chosen for all thermal images in this study. The typical thermal image obtained using the infrared camera used in this study is shown in Fig. 3(b).

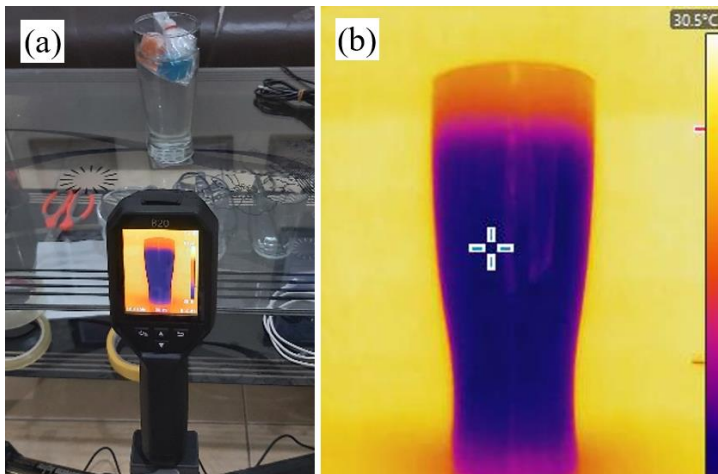


Fig. 3. Visualization of cold water inside the glass using an infrared camera (a) camera setup and (b) typical image obtained from the camera.

2.4 Supporting equipment

The experiments were conducted using 4 types of glasses that are typically used for serving drinks in Indonesia, glass A, glass B, glass C, and glass D (Fig. 4). Glass C and D are usually used for serving hot drinks as they have handles for holding the glasses when they are hot while the large diameter of both glasses allows hot drinks to cool faster. Glass B can be used for serving either cold drinks or hot beverages, although serving cold drinks may not be preferred as it does not look appealing. Glass A is a typical glass

used for serving cold drinks. The long and slender shape of glass A would make ice cubes and drinks more interesting.

The water level and the average diameter of the glass when filled with 250 ml water are shown in Table 2. Most tests were performed using glass A as it is commonly used for serving cold drinks while the rest of the glasses were used once only when testing the effect of glass diameter on the thermal performance of the reusable ice cubes.

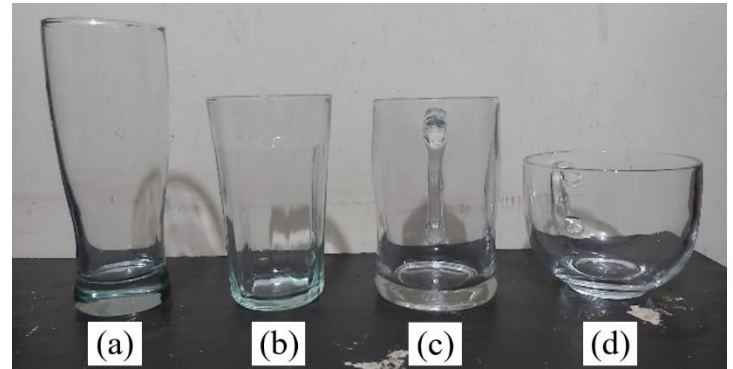


Fig. 4. The type of glasses used for the experiments are (a) glass A, (b) glass B, (c) glass C, and (d) glass D.

Table 2. The properties of each glass type used for the experiments

Glass Type	A	B	C	D
Water Level (mm)	112	97	72	43
Average Diameter (mm)	53	57	66	86



Fig. 5. The equipment setup for testing the reusable ice cubes.

DS18B20 sensors were placed carefully inside the glass. to ensure the accuracy of the temperature readings, the sensor locations were far enough from the water surface where the ice cubes were located. They were placed near the bottom of the glass but not touching the bottom surface. Duct tape was applied to attach the sensors at the determined location inside the glass. Paper tapes with glass numbers written on them were attached to each wire of the sensors to mark the reading from each sensor. The typical setup for the experiment during the test with the laptop, the Arduino temperature measurements, and the infrared camera is shown in Fig. 5.

2.5 Testing procedure

Before the cooling performance tests of the reusable ice cubes can be performed, the whole equipment and instrument are required to be tested and calibrated. The preliminary tests were performed to mark DS18B20 sensors with the correct number according to each glass. After that, the software that runs Arduino on the computer was checked if it produced correct readings. The detailed calibration and testing procedure was given by Luthfi [13].

The use of water ice cubes as a reference of how good the thermal performance of the ice cubes was problematic. Similar to the work of Luthfi et al. [14], to avoid unrealistic readings, water ice cubes were covered in a clear plastic bag. This treatment would prevent the melted ice diluted with the water inside the glass. As plastic bags would also become an additional thermal resistance to

the cooling process, the other types of ice cubes tested must also have a similar condition and must be placed inside plastic bags too.

Unlike stainless steel ice cubes which sink at the bottom of the glass, reusable plastic ice cubes float on the water surface. Hence, the self-stirring effect naturally occurs inside the glass due to natural convection effects where cold water near the ice cubes on the surface becomes denser and gradually sinks to the bottom. However, when performing comparisons with stainless steel ice cubes, they were hung on the water surface in order to produce the self-stirring effect.

Table 3. The value range of tested variables

Test No	Specimen	Ice Cube Quantity	Volume of Water (ml)	Glass Type
1	Local plastic	2	250	A
	Japan plastic	2	250	A
	Water ice cube	2	250	A
2	Local Plastic	2	250	A
	Stainless steel	2	250	A
	Water ice cube	2	250	A
3	Local plastic	1	250	A
	Local plastic	2	250	A
	Local plastic	3	250	A
	Local plastic	4	250	A
4	Local plastic	1	150	A
	Local plastic	1	200	A
	Local plastic	1	250	A
	Local plastic	1	300	A
5	Local plastic	1	250	A
	Local plastic	1	250	B
	Local plastic	1	250	C
	Local plastic	1	250	D

The experiments were prepared to be conducted in several series to compare different types of reusable ice cubes and to investigate the effects of the ice cubes quantity, the amount of water, and the diameter of the glass used. To avoid the test results becoming too complicated with too many lines in one graph, the tests of the ice cubes were divided into 5 series. When performing tests, the temperatures from all sensors were recorded every 10 s. The detailed information for each test series is given in Table 3.

As the equipment used in this experiment has limitations, there are of course uncertainties that come with the measurements. The error from using DS18B20 thermocouple sensors with Arduino microcontroller is estimated to be less than 1 °C while HIKMICRO B20 thermal camera has an accuracy of ± 2 °C. These limitations are indeed included in the analysis and considered in interpreting the results.

3. Results and discussion

3.1 Cold water temperature development

The unsteady temperature development of cold water inside the glass filled with reusable plastic ice cubes is shown in Fig. 6. Initially, cold temperatures were detected inside the glass as the purple color was different from the yellow color of the ambient. The comparison of the minimum temperature as plotted in Fig. 9(a) further confirms that stainless steel ice cubes produced the lowest minimum temperature of 22.0 °C compared to 23.375 °C and 22.75 °C obtained from using local plastic ice cubes and water ice cubes, respectively. On the other hand, local plastic ice cubes required 22.17 minutes to reach the lowest temperature which was the slowest compared to 11.0 minutes and 8.5 minutes from using stainless steel ice cubes and water ice cubes (Fig. 9(b)).

temperature. 10 minutes after recorded as shown in Fig. 6(a), the existence of the water surface inside the glass has not been observed yet as it was purple in all parts of the glass except a small area at the top right corner. The minimum temperature at this stage

was near the middle height of the glass. In the next 2 minutes, the cold part of the glass was developed with the minimum temperature located slightly higher and the surface of the water inside the glass started to be seen (Fig 6(b)). In the next stages of cold-water development from 14 to 24 minutes after recorded (Fig. 6(c)-Fig. 6(e)), the cold-water area inside the glass became more prominent with a clear boundary between the water and the air inside the glass and the location of the minimum temperature gradually increased. At the end image recorded process after 62 minutes, the water inside the glass became less cold with the minimum temperature located near the bottom of the glass (Fig. 6(f)).

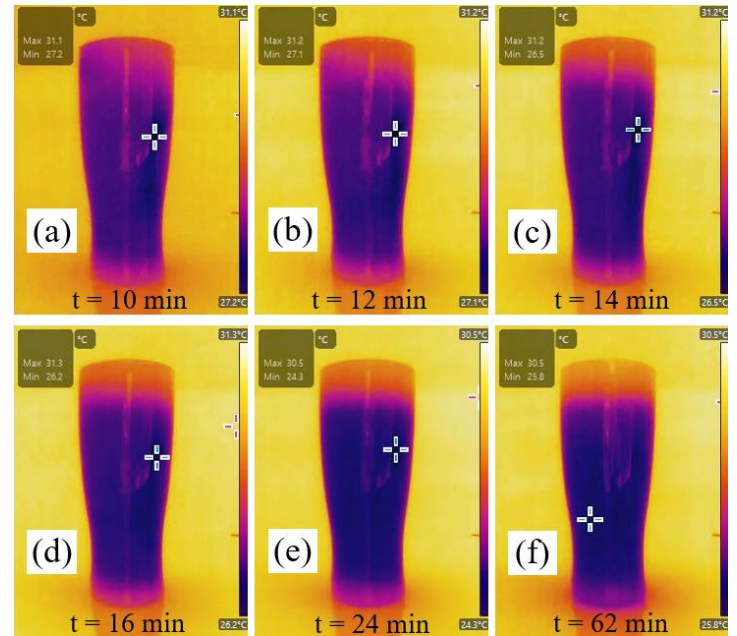


Fig. 6. Cold temperature development inside a type A glass filled with reusable plastic ice cubes.

3.2 Plastic ice cubes vs stainless steel ice cubes

The evolution of water temperature inside the glass as plotted in Fig. 7 shows that each ice cube type affects the water in a different trend. It is obvious that local plastic ice cubes decrease the water temperature more slowly and they require more time to reach the minimum temperature compared to other types of ice cubes. However, the minimum temperature obtained from using these ice cubes is lower than water ice cubes. On the other hand, stainless-steel ice cubes cool the water as quickly as water due to their higher thermal conductivity.

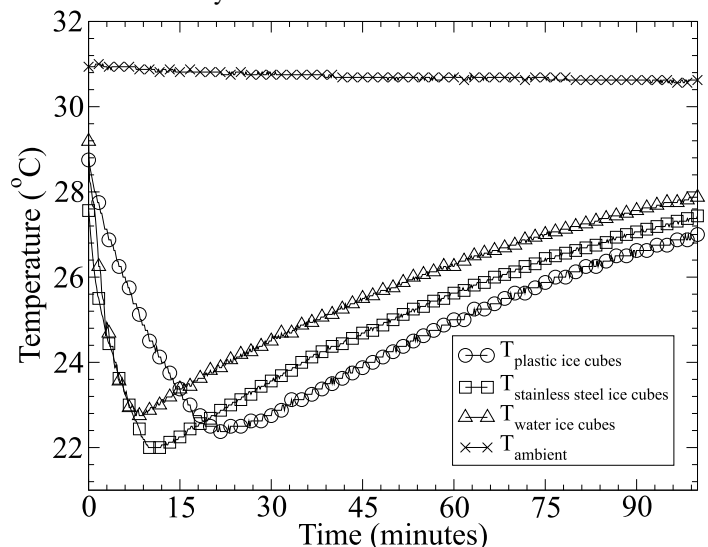


Fig. 7. The comparison of the time series of water temperature inside type A glass between plastic ice cubes with other types of ice cubes, stainless steel, and water ice cubes.

The minimum temperature obtained from using stainless steel ice cubes was the lowest compared to other types of ice cubes, although the temperature of water quickly rose higher than the temperature of water from using local plastic ice cubes. Overall, the temperature of water using the local plastic ice cubes is the lowest although the minimum temperature was from using stainless-steel ice cubes.

The contour plot of the glass taken during the test in Fig. 8 shows the detailed temperature distribution of water around the glass and it confirms the temperature evolution plot in Fig. 7.

The contour plot of the glass filled with local plastic ice cubes shown in Fig. 8(a) shows the deepest purple color compared to other glasses while in Fig. 8(b), the glass filled with stainless steel ice cubes was not as cold as plastic ice cubes but colder than water ice cubes. It appears that the PCM liquid inside both reusable ice cubes has lower freezing temperatures and can maintain lower temperatures longer than plain ice without any additives.

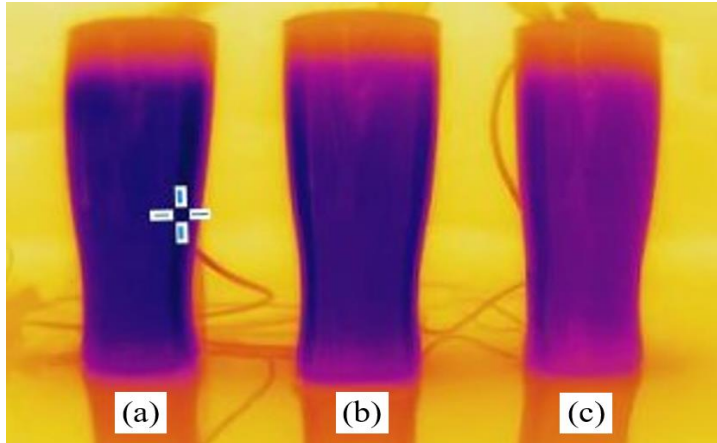


Fig. 8. The comparison of temperature contour plots of water in a type A glass filled with (a) local plastic ice cubes, (b) stainless-steel ice cubes, and (c) water ice cubes.

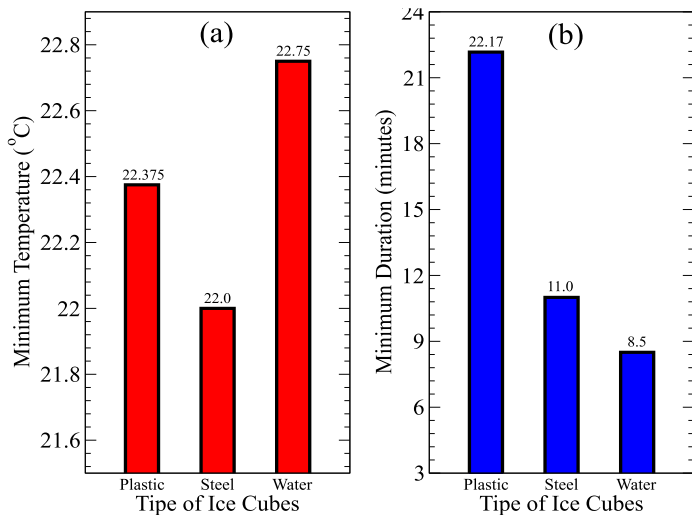


Fig. 9. The comparison of cooling performance of various types of reusable ice cubes, (a) minimum temperatures, and (b) minimum time.

3.3 Plastic ice cube comparison

The time evolution plot of temperature for local plastic ice cubes, Japanese brand ice cubes, and water ice cubes as shown in Fig. 10 proves that the price of the ice cubes does play an important role in the thermal performance of reusable plastic ice cubes. The more expensive Japanese brand plastic ice cubes not only reach a lower minimum temperature but also do it quicker than local plastic ice cubes, although they are not as quick as water ice cubes. Overall, the temperatures of water that use Japanese brand plastic ice cubes are lower than that of local plastic ice cubes. The Japanese brand plastic ice cubes possibly applied better and more expensive PCM

ingredients or they might be made from better quality plastic that results in better thermal performance.

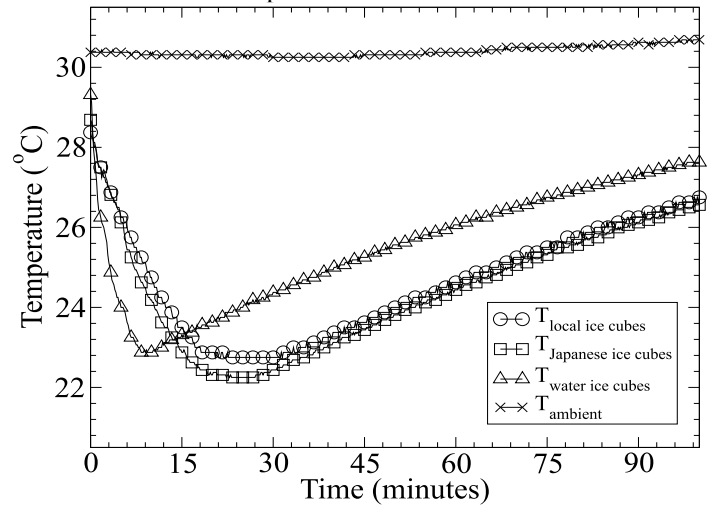


Fig. 10. The comparison of the time series of water temperature inside type A glass filled with different types of plastic ice cubes.

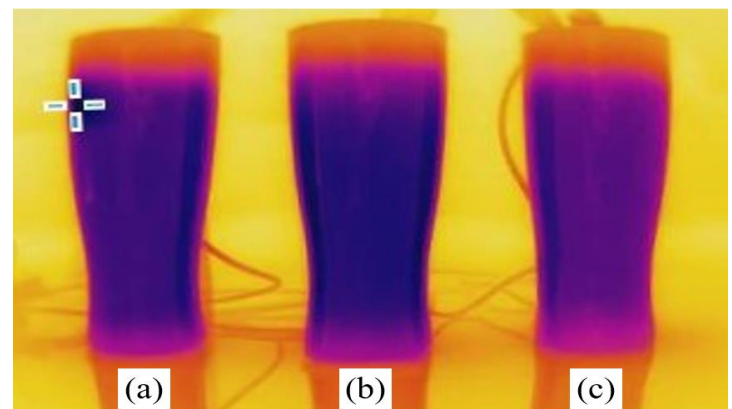


Fig. 11. The comparison of temperature contour plots of water in a type A glass filled with (a) local plastic ice cubes, (b) Japanese brand plastic ice cubes, and (c) water ice cubes.

The contour plots of glasses used in this test series as shown in Fig. 11 also show that the glass filled with Japanese brand ice cubes (Fig. 11(b)) is the coldest with the deepest purple color compared to other glasses, although the difference with the color of the glass filled with local plastic ice cubes (Fig. 11(a)) is less obvious. In order to see the thermal performance difference between all types of ice cubes tested in this test series, the minimum temperature and the time required to reach the minimum temperature in Fig. 10 were extracted and plotted separately in Fig. 12.

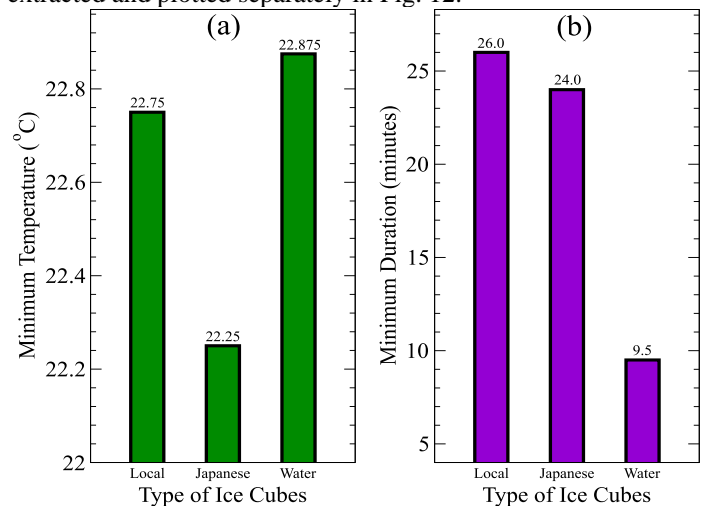


Fig. 12. The comparison of cooling performance of various types of plastic ice cubes with water ice cubes as a reference, (a) minimum temperatures, (b) minimum time.

From the cooling performance of ice cubes as plotted in Fig. 12 it is obvious that the lowest minimum temperature was 22.25 °C obtained by using Japanese brand ice cubes. Followed by local plastic ice cubes and water ice cubes with minimum temperatures of 22.75 °C and 22.875 °C, respectively. On the other hand, the quickest minimum time required to reach the minimum temperature was 9.5 minutes obtained by using water ice cubes. Japanese brand ice cubes were quite fast with a minimum time of 24 minutes while the local plastic ice cubes were the slowest with a minimum time of 26 minutes.

3.4 The number of ice cube influence

The test series performed in investigating the effect of the number of local plastic ice cubes used was performed using 250 ml water filled in type A glasses with the number of ice cubes tested varied from one to four ice cubes. The temperature development of water inside the glass as plotted in Fig. 13 shows that the water temperatures initially drop to minimum temperatures before slowly increasing to ambient temperatures. It is obvious that increasing the number of ice cubes used will significantly decrease the temperature of the water, especially the minimum temperatures, although the minimum temperatures were reached at a longer time for glasses containing more ice cubes.

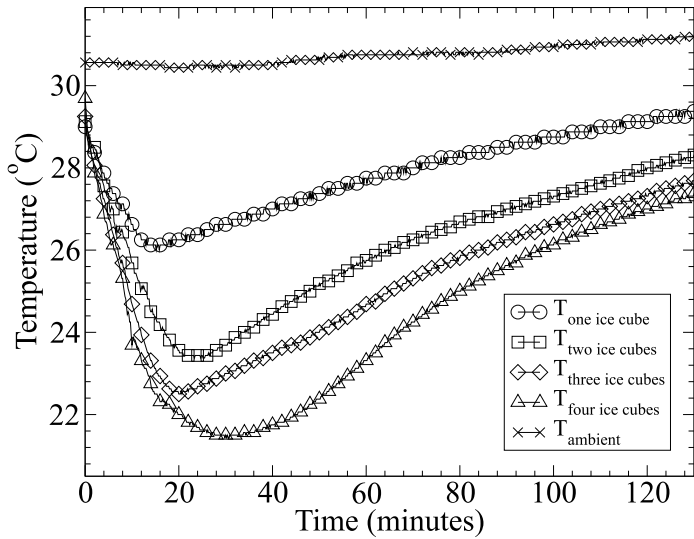


Fig. 13. The effect of varying the number of local plastic ice cubes on the time evolution of water temperature inside a type A glass filled with 250 ml of water.

The temperature contour of the glasses in this test series as shown in Fig. 14 supports the trend of the temperature readings in Fig. 13. The temperature contour plots also provide a more detailed view of the temperature distribution of water inside the glasses. All the glasses show the water surface clearly and a deeper purple color is observed from glasses filled with more ice cubes.

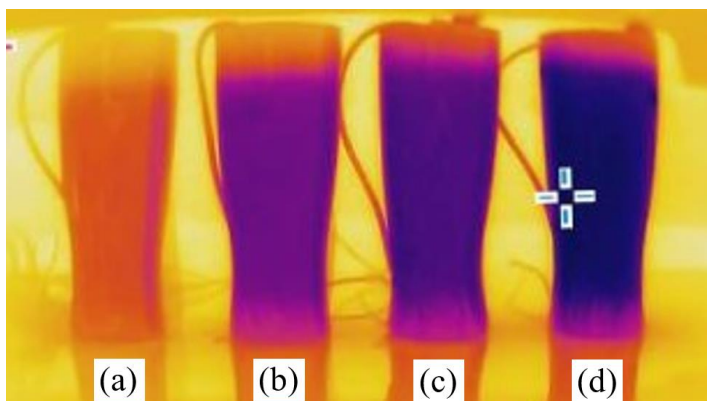


Fig. 14. The comparison of temperature contour plots of water in a type A glass filled with (a) one, (b) two, (c) three, and (d) four plastic ice cubes.

To further analyze the relationships between the number of ice cubes N , the data of the minimum temperatures, T_{min} were extracted from Fig. 13 and plotted in Fig. 15(a). It can be seen from the figure that the minimum temperatures drop as the number of ice cubes increases. Careful examination of the trend of the data and by performing curve fitting by trial and error, the best fit for the data as shown in Fig. 15(b) was obtained by using a power of $-1/5$.

The equation resulting from the linear regression of the number of ice cubes on a scale can be seen in Eq. (1). The accuracy of the fitting line for the minimum temperature data as shown in Fig. 15(b) is excellent with an accuracy of 0.9997088.

$$T_{min} = 8.3798 + 17.641 \cdot N^{-1/5} \quad (1)$$

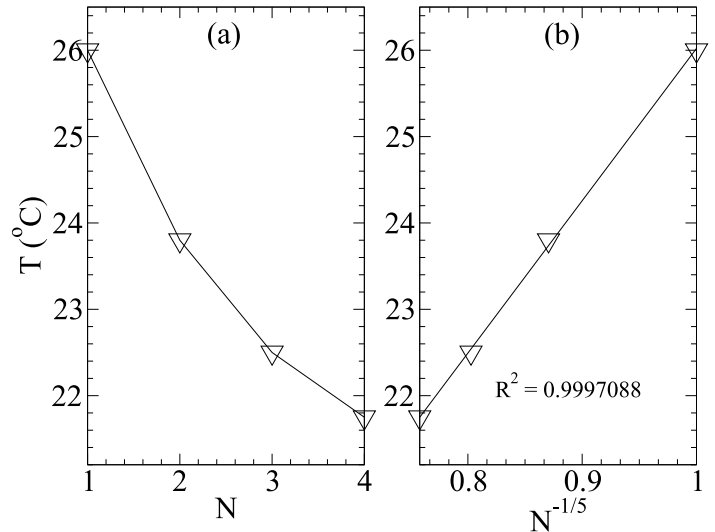


Fig. 15. The minimum temperature of the water inside type A glass as a function of the number of ice cubes used, (a) raw data, and (b) scaled data.

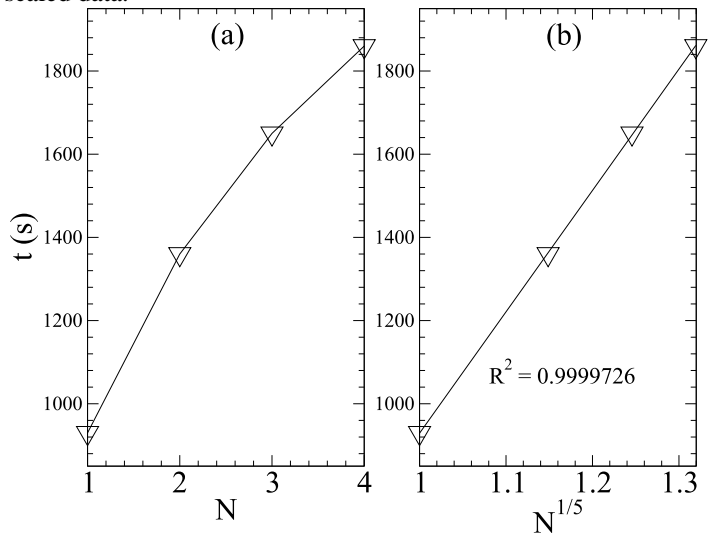


Fig. 16. The minimum time required to reach the minimum temperature as a function of the number of ice cubes used, (a) raw data, and (b) scaled data.

On the other hand, the data for the minimum time, t_{min} as plotted in Fig. 16, show the opposite trend with t_{min} increasing when using more ice cube quantity, N . The rate at which the minimum time increases, is reduced at a larger quantity of ice cubes used and it creates a non-linear data trend. By performing careful searching by trial and error, it was found that the data for the minimum time can be best fitted by applying a power of $1/5$ to N . The curve fitting process using the linear regression method produces a very accurate fit curve with an accuracy level of 0.9999726 and the resulting equation can be seen in Eq. (2).

$$t_{min} = -1988.6 + 2917.8 N^{1/5} \quad (2)$$

3.5 The volume of water influence

For investigating the effect of the amount of water inside the glass, the volume of water is varied from 150 ml to 300 ml. This test series also employed four type A glasses with two local plastic ice cubes in each glass. The time series of water temperature obtained from DS18B20 sensors as plotted in Fig. 17 shows that both the minimum temperatures and the time required to reach the minimum temperature are affected by the amount of water inside the glass. As can be seen from the figure, the minimum temperatures drop when the volume of water increases due to the same number of ice cubes used inside the glass having to cool a larger amount of water. The temperatures quickly rise as soon as the minimum temperatures are obtained and then slowly approach the ambient temperature.

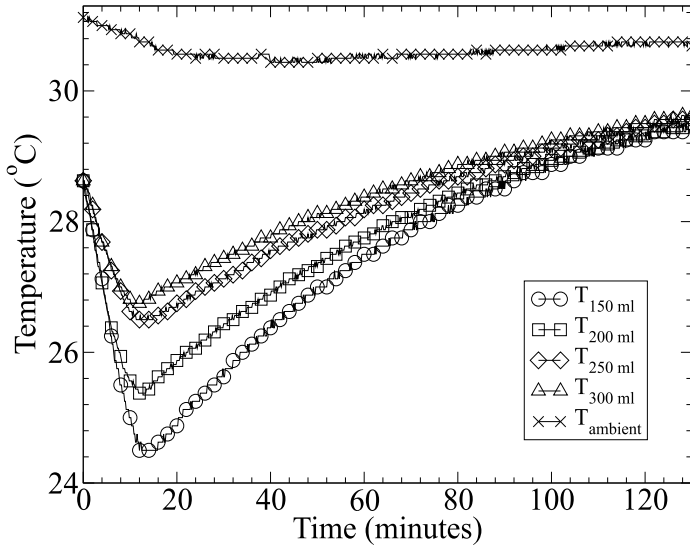


Fig. 17. The effect of varying the volume of water on the time evolution of water temperature inside a type A glass filled with one local plastic ice cube.

The thermal image taken in this test series as shown in Fig. 18 visualizes the detailed temperature distribution around the glasses and the water inside the glasses.

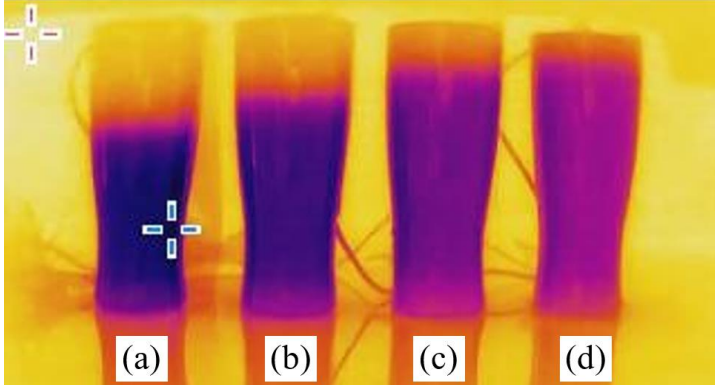


Fig. 18. The comparison of temperature contour plots of water in a type A glass filled with (a) 150 ml, (b) 200 ml, (c) 250 ml, and (d) 300 ml of water.

It supports the trend of the temperature readings in Fig. 17. The glasses with less amount of water show colder water temperature with a deeper purple color. The lowest minimum temperature from the thermal image taken was observed in the glass filled with 150 ml water.

Similar to the effect of the number of ice cubes, N in the previous section, the minimum temperature data, T_{min} for each glass shows a non-linear relationship when plotted against the volume of water, V (Fig. 19(a)). In order to find out the trend of the data, repeated trial and error tests were performed and it was found that a power of $1/3$ applied to the volume of water, V would perfectly fit all the minimum temperature data. The linear regression curve

method applied to a scaled water volume as shown in Figure 19(b) will yield Eq. (3).

$$T_{min} = 15.826 + 1.633 \cdot V^{1/3} \quad (3)$$

This equation is very accurate and it can fit all the data with an accuracy of $R^2 = 0.9999634$.

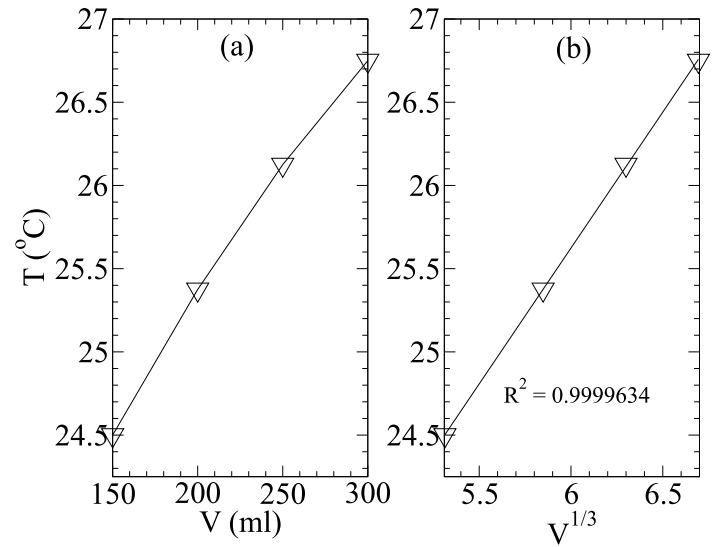


Fig. 19. The minimum temperature of water inside type A glass as a function of the volume of water, (a) raw data, and (b) scaled data.

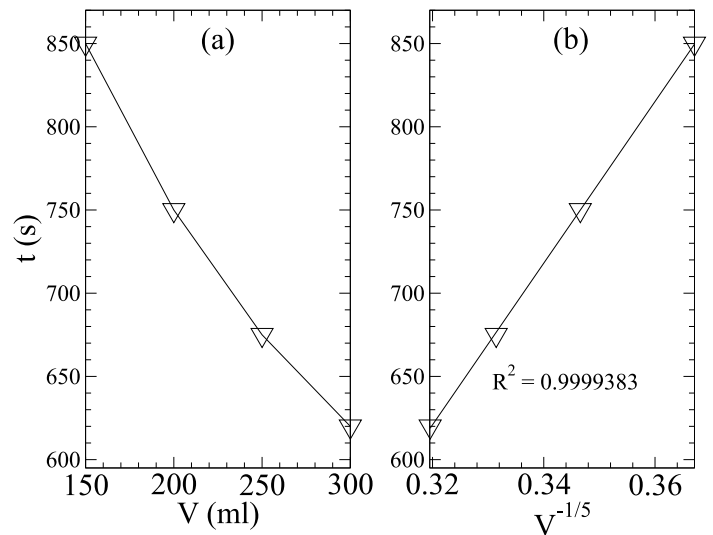


Fig. 20. The minimum time required to reach the minimum temperature as a function of the volume of water, (a) raw data, and (b) scaled data.

Increasing the volume of water inside the glass has the opposite effect on the minimum time required to reach the minimum temperature. The minimum time decreases with a larger amount of water poured inside the glass. As can be seen in Fig. 20(a), the rate at which the minimum time decreases reduces at a high volume of water used, thus it creates a non-linear relationship. By performing repeated trial and error searching, the best fit that will alter the non-linear line into a linear line was obtained by using a power of $-1/5$. The curve fitting process performed on the scaled data using a linear regression method produces an excellent fit with an accuracy of 0.9999383 (Fig. 20(b)). The equation can be seen in Eq. (4).

$$T_{min} = -932.99 + 4856 \cdot V^{-1/5} \quad (4)$$

3.6 The glass diameter influence

To investigate the effect of glass diameter, four types of glass were used, and 250 ml water with two local plastic ice cubes were filled in each type of glass. Detailed information about all glasses used in this test series is given in Table 2. The temperature

development over time as plotted in Fig. 21 shows that the effect of glass diameter is less obvious compared to the other effect tested in this study. To make the graph more differentiable and observable, the symbol used for each data had to be made smaller, and the lines were removed. In general, the increase in glass diameter will also increase the minimum temperatures except for type D glass where the temperature readings show an abnormal trend. Similar to Luthfi et al. [14], here there was also a problem with type D glass where the glass was too wide making the water level too shallow that the temperature sensors became too close to the ice cubes. Hence, the temperature sensor readings were more likely to underestimate the water temperature. In subsequent analysis, the data from type D glass will be excluded.

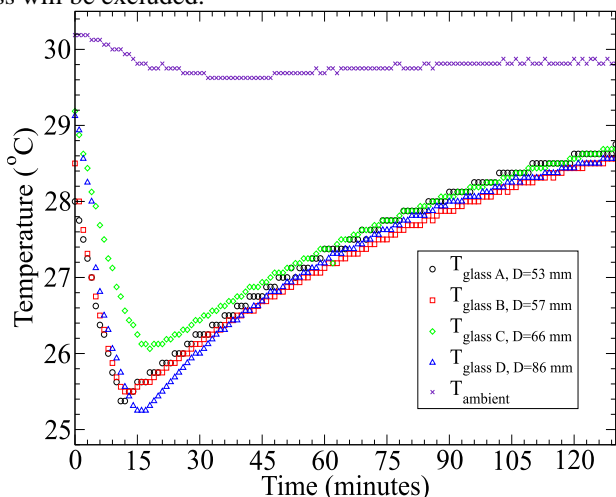


Fig. 21. The effect of varying glass diameter on the time series of water temperature inside various types of glasses filled with a local plastic ice cube.

From the thermal image taken during this test series as shown in Fig. 22, it is hard to tell which one is colder than the other. From careful examination, it appears that glass B and glass D are colder than other glasses but only slightly colder.

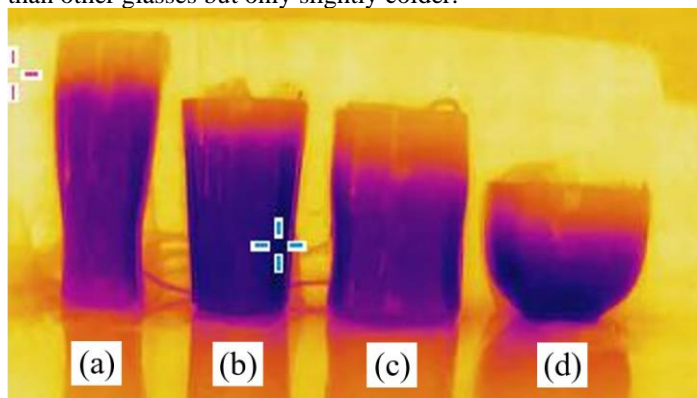


Fig. 22. The comparison of temperature contour plots of 250 ml of water filled in a (a) type A glass, (b) type B glass, (c) type C glass, and (d) type D glass.

It is important to note that the thermal image was not taken at the minimum temperature. Since the minimum time to reach the minimum temperature is different among each type of glass, it is not possible to compare the thermal image at a precise minimum temperature. Having a close look at the final temperature reading in Fig. 21, it is correct that the final temperatures of glass B and glass D are lower than other glasses.

To see the effect of the glass diameter more clearly, the minimum temperatures and the time required to reach the minimum temperature for type A, B, and C glasses are extracted from Fig. 21 and plotted separately in Fig. 23 and Fig. 24. The relationships between the minimum temperatures and the glass diameter appear to be almost linear. However, if the linear regression method were used in the curve fitting process, the accuracy of the fitting curve is not very good.

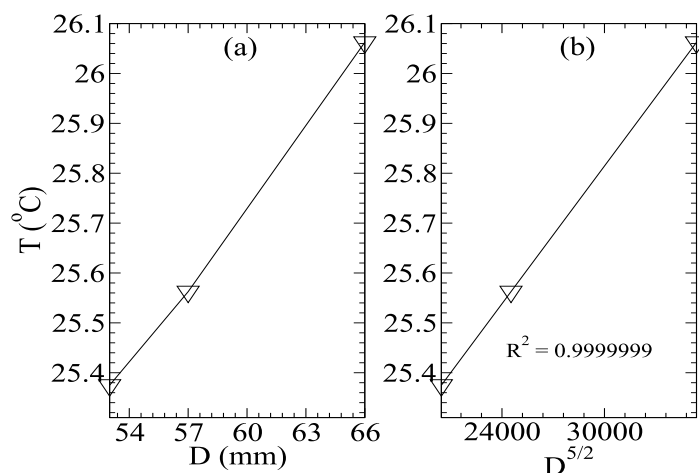


Fig. 23. The minimum temperature of water as a function of glass diameter, (a) raw data, and (b) scaled data

By performing repeated trial and error searches, a power of 5/2 applied to the glass diameter, D would result in a very high accuracy curve fitting. The linear regression method applied to the scaled glass diameter will have an R^2 accuracy of almost 1 and the equation can be seen in Eq. (5).

$$T_{min} = 24.434 + 4.6027 \times 10^{-5} D^{5/2} \quad (5)$$

The minimum time required to reach the minimum temperature as plotted in Fig. 24(a) increased with the larger glass diameter used. It is obvious that the data of the minimum time, t_{min} when plotted against the glass diameter, D creates a nonlinear line.

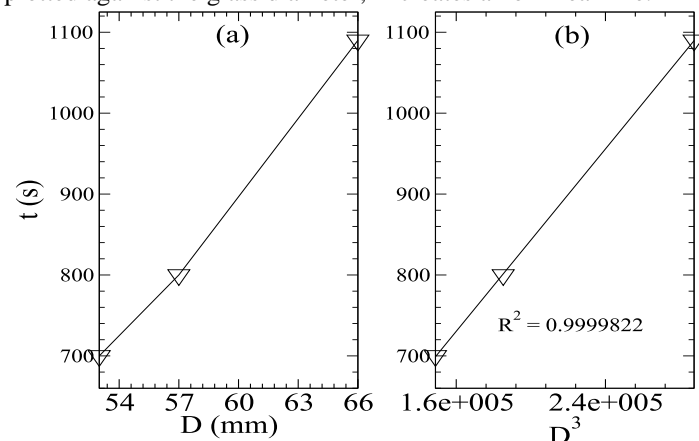


Fig. 24. The minimum time required to reach the minimum temperature of water as a function of glass diameter, (a) raw data, and (b) scaled data.

By performing repeated testing by trial and error, it was found that the best fit with an $R^2 = 0.9999822$ can be obtained by using a power of 3. The equation obtained from performing the curve fitting process using the linear regression method on the scaled glass diameter can be seen in Eq. 6.

$$T_{min} = 279.46 + 0.0028181 \cdot D^3 \quad (6)$$

3.7 Empirical relationships

Eqs. (1), (3), and (5) can be combined to obtain a single equation that can estimate the minimum temperature of the water inside a glass filled with plastic ice cubes, T_{min} as a function of the ice cubes quantity N , the amount of water V , and the diameter of the glass used D . With $T_{min} \sim N^{1/5}$ from Eq. (1), $T_{min} \sim V^{1/3}$ from Eq. (3), and $T \sim D^{5/2}$ from Eq. (5), the combined equation will be $T_{min} \sim N^{1/5} V^{1/3} D^{5/2}$. The procedure for generating the combined equation was performed according to the method used by Luthfi et al. [14]. All equations in this paper were obtained from a linear regression curve fitting process using scaled parameters that have a general form as follows,

$$Y = a + bX^c \quad (7)$$

Where a, b, and c are constants that were determined from experimental data. Constant c is the power that was used to alter the equations from nonlinear to linear while constant b is the slope of the linear lines and a is the constant that determines how far the lines are from the X and the Y axis. The combined equation will take an average of the constants a and b and the empirical equation will have a final form of

$$Y = m + nX_{combined} \quad (8)$$

To ensure all the data points from Eqs (1), (3), and (5) lie on the same line, the constants m and n were repeatedly adjusted by trial and error. The curve-fitting process using linear regression on all adjusted data points as shown in Fig. 25 would result in an equation that combined all parameters as follows,

$$T_{min} = 8.47 + 4.97 \times 10^{-5} \frac{V^{1/3} D^{5/2}}{N^{1/5}} \quad (9)$$

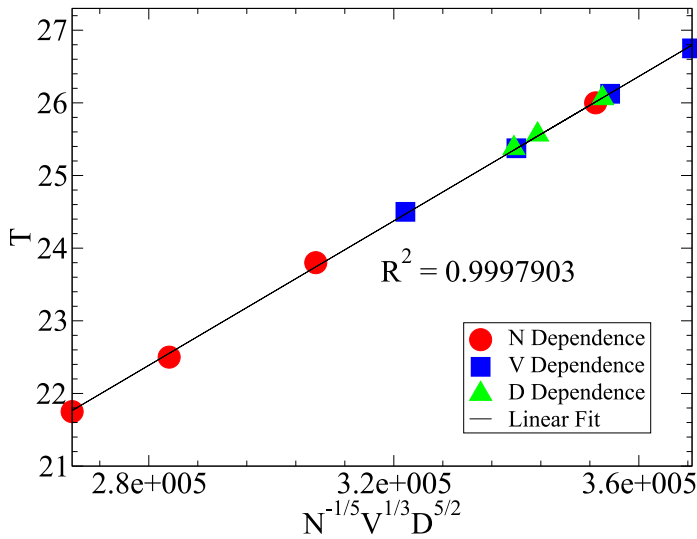


Fig. 25. The combined influence of all contributing parameters to the minimum temperature

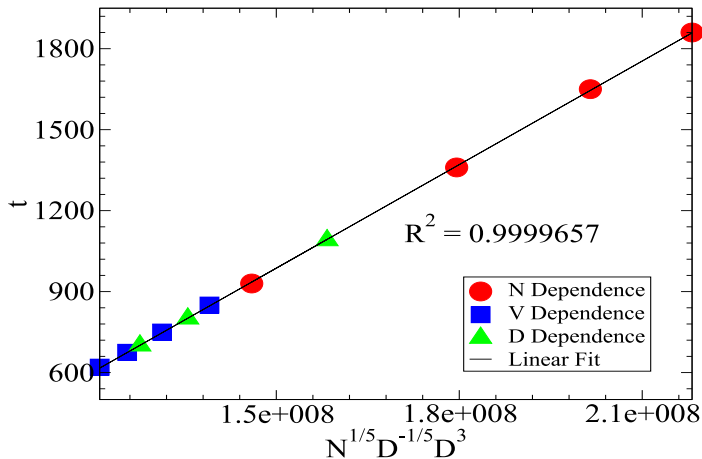


Fig. 26. The combined influence of all contributing parameters to the time required to reach the minimum temperature

The same procedure can be applied to generate a single equation that can predict the minimum time required to reach the minimum temperature, t_{min} as a function of the number of ice cubes N , the volume of water V , and the glass diameter D , by using Eqs (2), (4), and (6). With $t_{min} \sim N^{1/5}$ from Eq. (2), $t_{min} \sim V^{-1/5}$ from Eq. (4), and $t_{min} \sim D^3$ from Eq. (6), the combined equation will be $t_{min} \sim N^{1/5} V^{-1/5} D^3$. By repeatedly trial and error adjusting the constants m and n required, the combined equation for predicting the minimum time can be written as follows,

$$t_{min} = -931 + 1.28 \times 10^{-5} \left(\frac{N}{V}\right)^{1/5} D^3 \quad (10)$$

T_{min} in Eq. (9) and t_{min} in Eq. (10) are calculated in °C and in s with V in ml and D in mm while N is dimensionless.

4. Conclusions

This study presents a comparative thermal performance analysis of various commercially available reusable ice cubes, employing DS18B20 thermocouple sensors for temperature measurement and HIKMICRO B20 thermal imaging for visualization of temperature distribution. The results demonstrate that:

1. Stainless steel ice cubes cool water faster due to their higher thermal conductivity, while plastic ice cubes can achieve lower minimum temperatures.
2. Ice cube brand quality influences thermal performance, with higherpriced Japanese plastic ice cubes cooling water more efficiently than their lower-cost counterparts.
3. The number of ice cubes (N), water volume (V), and glass diameter (D) significantly impact cooling efficiency.
4. The empirical relationships derived show that increasing N decreases the minimum temperature, $T_{min} \sim N^{-1/5}$ and increases the cooling time, $t_{min} \sim N^{1/5}$.
5. Increasing V results in a higher minimum temperature $T_{min} \sim V^{1/3}$ and a shorter cooling time $t_{min} \sim N^{1/5}$.
6. The glass diameter (D) has a less pronounced effect but contributes to an increase in both the minimum temperature $T_{min} \sim D^{5/2}$ and cooling time $t_{min} \sim D^3$.

These findings provide valuable insights into the cooling efficiency of reusable ice cubes, aiding in the selection of optimal designs for specific cooling applications in the food industry and beyond. Future research could explore the long-term durability, environmental impact, and heat transfer mechanisms of reusable ice cubes under various real-world conditions..

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