Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin
e-ISSN : 2549-1999 No. : 4 Month : August
p-ISSN : 1693-5462 Volume : 21 Year : 2023

Article Processing Dates: Received on 2023-06-04, Reviewed on 2023-08-11, Revised on 2023-08-17, Accepted on 2023-08-18 and Available online on 2023-08-25

Thermal analysis and thermography observation of stainless-steel ice cubes

Luthfi[1*], Azhar[2], Zuhaimi[1], Syamsuar[1], Sumardi[1]
[1]Department of Mechanical Engineering, Politeknik Negeri Lhokseumawe, Lhokseumawe 24301, Indonesia
[2]Department of Electrical Engineering, Politeknik Negeri Lhokseumawe, Lhokseumawe 24301, Indonesia
*Corresponding author: luthfi@pnl.ac.id

Abstract

Alternative products for water ice cubes have long been sought due to the spread of waterborne diseases and microplastic contamination, as they are often made from unhygienic water sources. Recently, stainless-steel ice cubes have been considered as one of the best alternatives, and they have been very popular in marketplaces, although very few studies found in the literature that have investigated their potential in replacing water ice cubes. In this study, the thermal performance of stainless-steel ice cubes will be explored experimentally using a combination of an Arduino microcontroller equipped with DS18B20 thermocouple sensors and a HIKMICRO B20 thermal camera with the aim to find out how good stainless steel ice cubes for cooling food and beverages. The time evolution of water temperature in glasses filled with stainless-steel cubes of various brands is compared with that of water ice cubes. The temperature field obtained from thermal images is used to further observe the overall temperature of water in the glass. Leeseph stainless-steel ice cubes are found to have thermal performance comparable to water ice cubes, while SSGP ice cubes can retain lower temperatures for a longer time compared with other ice cubes. The effect of the number of ice cubes (N), the volume of water (V), and the average diameter of the glass used (D) are also investigated. At $1 \leq N \leq 4$, the larger number of ice cubes used are found to lower the minimum temperature, $T \sim N^{-1/5}$ and to decrease the minimum time, $t \sim N$ while at 150 ml $\leq V \leq$ 300 ml, the larger amount of water used are observed to increase the minimum temperature $T \sim V^{1/5}$ and to increase the minimum time, $t \sim V$. At 53 mm $\leq D \leq$ 66 mm, larger glass diameter used are found to increase both the minimum temperature, $T \sim D$ and the minimum time, $t \sim D$.

Keywords:
Ice cubes, stainless-steel, Arduino, DS18B20, thermal images.

1 Introduction

Water ice cubes have long been used in the food and beverage industry since refrigeration technology was first invented. They have been popular as they are simple to produce and easy to use. Rectangular shape water ice cubes can be made on a small scale in a domestic refrigerator using an ice cube tray or mass-produced using an industrial-scaled refrigeration system.

Ice cubes would usually be mixed directly with food or beverages, and the cooling effect was obtained by the heat transfer from the ice cubes and the mixing with the melted liquid from the ice cubes. Although it is common practice these days, cooling food and beverages with this method obviously has drawbacks. First, the water from the melted ice cubes will dilute the food/drink and reduce the taste. Besides that, ice cubes made from water only would melt quickly in hot summer weather. In many developing countries, the use of water ice cubes has been suspected as the cause of spreading water-borne diseases since they are often made from unhygienic water. Izani et al. [1] found that the ice cubes sampled from canteens in Kelantan, Malaysia, were contaminated by faecal coliforms. Shruti et al. [2] also observed a similar phenomenon, and they suggested that ice cubes might get contaminated by microplastics.

Instead of using water ice cubes, alternative ways of cooling food and beverages have been proposed and suggested in the literature. Reusable ice cubes are considered one of the best alternatives to overcome the weaknesses of water ice cubes, and there have been many types of reusable ice cubes available in the market. Reusable ice cubes are also expected to reduce the cost of cooling in the long term as they can be reused. Zou et al. [3] created reusable ice cubes from gelatin hydrogel, which are named “jelly ice cubes” (JICS). They suggested that JICS can prevent cross-contamination that often occurs in water ice cubes. They tested their ice cubes and found that JICS containing 10% gelatin hydrogel can absorb and release 265.35 J/g latent heat of fusion with cooling efficiency comparable to water ice cubes. JICS was also tested to withstand normal pressure equivalent to 1 m food load while the properties of JICS can remain stable for at least five reuse cycles. In order to find out any structural instability of JICS due to temperature change, they further tested their ice cubes under various freezing and thawing conditions [4]. They applied extreme freezing conditions from -20 ºC to -198 ºC, with thawing rates ranging from 0.05 ºC/min to 25 ºC/min. They found that JICS remains stable after at least ten freezing-thawing cycles.

Most reusable ice cubes that are commercially available in the market take advantage of using Phase Change Material (PCM) to increase the thermal performance of the ice cubes. The study of PCM as heat storage has been widely available in the literature. Ezan et al. [5] put PCM blocks of various thicknesses ranging from 2 to 10 mm inside a Vertical Beverage Cooler (VBC) to reduce energy consumption and to improve thermal stability and flow characteristics inside the cooler. They used Computational Fluid Dynamics (CFD) software ANSYS-FLUENT to simulate the flow inside the cooler. A two-dimensional (2D) lump model with a dedicated user-defined function (UDF) was used in their numerical model to simulate the on/off controller. They found that the PCM blocks enhance cooling performance by extending the period of compressor off duration and by preventing sudden temperature increases. Oro et al. [6] reviewed broader applications of PCM for energy storage purposes. They summarized the properties of various PCM materials with melting temperatures of less than 20 ºC. Of the 88 PCM materials listed in the tables, 40 are commercial materials available in the market. They also discussed the potential problems that might occur when using the PCM material listed in their tables, such as corrosion, phase segregation, and stability in long-term use or extended cycles. They suggested that the field area that can take advantage of the reviewed PCM materials were very diverse such as cold storage, air conditioning, or refrigerated trucks.

Further applications of PCM materials for thermal energy storage purposes, especially at medium temperatures, were reviewed by Pereira da Cunha and Eames [7]. They summarized the thermal energy storage properties of various types of PCM materials that are classified into three categories: organic compounds, salt hydrates, and eutectic compounds. They suggested that for energy storage applications at temperatures below 100 ºC, organic compound, and salt hydrates PCM will give the best performance, while for applications that operate at temperatures of more than 100 ºC, they recommended using eutectic compound PCM. PCM materials that are specifically used for refrigeration systems were reviewed by Selvness et al. [8]. They classified PCM materials based on temperature and applications, such as for air conditioning at 20 ºC or for freezing food products at -60 ºC. They summarized various research and new technology on thermal energy storage PCM materials, which were listed in a table at temperatures ranging from 10 ºC to -65 ºC.

The study of PCM materials that are specifically used for ice cubes are hardly found in the literature. The most relevant one is the study of reusable ice cubes conducted by Kumar et al. [9] which was motivated by hygienic issues of using water as ice cubes. They designed and manufactured the ice cubes by filling PCM material into metal casings. The PCM materials used in their ice cubes were a mixture of portable and distilled water with a salt and sugar solution. They tested their ice cubes and compared them with water ice cubes. They found that the thermal performance of their ice cubes was as good as water ice cubes.

Recently, Luthfi et al. [10] attempted to manufacture stainless steel ice cubes without using any PCM materials. They cut a piece of austenitic stainless 316 food grade into ice cubes of 25 mm × 25 mm × 25 mm with no PCM substance filled in it. They found that the thermal performance of the ice cube was not as good as water ice cubes. Luthfi [11] then purchased and investigated commercial stainless-steel ice cubes that contain PCM material inside them. He built microcontroller-based temperature measurement systems for more accurate calculations of the thermal performance of the ice cubes. He used an Arduino microcontroller equipped with DS18B20 thermocouple sensors for simultaneously measuring the transient temperature of water cooled by various types of ice cubes. He compared the thermal performance of commercial stainless-steel ice cubes purchased from the online market with custom stainless-steel ice cubes with no PCM material and water ice cubes. He still found that the thermal performance of custom stainless-steel ice cubes was not as good as water ice cubes. He suggested that using PCM inside the stainless-steel ice cubes is necessary as the commercial stainless-steel ice cubes performed almost as good as water. However, his results and conclusion were obtained based on temperature measurement only, which might not be convincing as the overall change in temperature, either the ice cubes or the water in the glass, was not visualized. Besides that, only one brand of commercial stainless ice cubes was tested.

Considering few studies have been done in investigating the thermal performance of commercial stainless ice cubes as discussed in previous paragraphs, in this study, more comprehensive tests on commercial stainless steel ice cubes that are available in the market will be conducted with the aim to obtain scientific and technical information on how good and how effective stainless steel ice cubes are when compared to water ice cubes. A couple of commercial stainless ice cubes from different brands and price ranges will be tested. The thermal performance calculations will not be based on temperature measurement only but also based on thermography observation using a thermal camera. The thermal performance analysis will also include the influence of the volume of water, the number of ice cubes, and the average diameter of the glass used.

2 Research Methods

The stainless-steel ice cubes used in this study were purchased online from Tokopedia. There were various brands of ice cubes tested. Water ice cubes were used to reference how well the stainless-steel cubes performed compared to a standard way of cooling food or drink using common water ice cubes. The water temperatures inside the glasses that were cooled using ice cubes were measured using DS18B20 thermocouples controlled by an Arduino microcontroller. The water and ice cube temperatures were visualized using the thermal images obtained using a thermal camera. The detail of the ice cube specimens used, the temperature measurement system, the visualization method, and the testing procedure will be discussed in the subsequent sub-sections.

2.1 Ice Cube Specimens Used

Leeseph brand stainless-steel ice cubes were chosen for testing the influence of volume of water, the glass average diameter, and the number of ice cubes since they were one of the most popular stainless-steel ice cube brands purchased by the customers at the online market Tokopedia. In order to find out if the price of stainless-steel ice cubes will affect the thermal performance of the ice cubes, two sets of premium price stainless-steel ice cube brands, SSGP and Remax, were purchased and tested for comparison. The images of stainless-steel ice cubes tested in this study are shown in Fig. 1, and the detailed information of the ice cubes for each brand can be seen in Table 1.

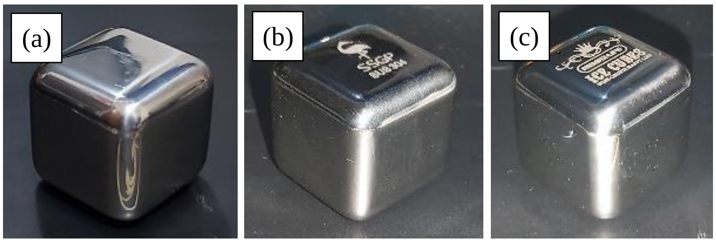


Fig. 1. Stainless-steel ice cubes of various brands (a) Leeseph, (b) SSGP, and (c) Remax.

Table 1. Stainless-steel ice cube specimens

Brand	Size	Price
Leeseph	25×25×25 mm	IDR 6,800/piece
SSGP	25×25×25 mm	IDR 14,800/piece
Remax	25×25×25 mm	IDR 15,500/piece

All ice cubes shown in Fig. 1 look almost identical, except SSGP and Remax have logos engraved on one side of the ice cube. As listed in Table 1, all ice cubes have an identical size which means specimen size will not be a problem for the testing and comparison in this study.

The detail thermal properties of stainless-steel ice cubes were not available as they were not given in the manual sheet inside the package. The detail PCM mixture inside the ice cubes were also not available and these were varied between brands. It appears that each ice cube manufacturers have their own secret ingredient. The only information given was the ice cubes were made of stainless-steel food grade 304 for all brands investigated. In this study, the thermal properties of stainless steel were taken from heat transfer textbook to be 16 W/(m.K) at room temperature and around 8 W/(m.K) at temperature below 0 ºC.

Before performing the experiment, all stainless-steel ice cubes were at room temperature of 31 ºC. Although the recommended freezing time from the manufacture is at around 14 hours, all ice cubes specimens used in the experiment were stored in a domestic refrigerator for at least two days or 72 hours.

2.2 Temperature Measurement System

For more accurate calculation and comparison of the thermal performance of the stainless-steel ice cubes, the temperature must be measured simultaneously in real-time. DS18B20 thermocouple sensors were chosen due to their high accuracy, water resistant, and the most crucial thing is the flexibility in setting up more than one sensor without taking extra ports in the Arduino microcontroller. DS18B20 thermocouple sensors have often been used before in similar studies found in the literature [12]–[14].

Before connecting to the Arduino microcontroller, all DS18B20 wires were set up on an 830 holes breadboard. An LCD 2×16 was used to monitor the temperature of the sensor. Arduino was connected to a computer using a USB cable. The components required for setting up the temperature measurement system using DS18B20 sensors are listed in Table 2. The detailed circuit and arrangement of the DS18B20 sensors on the breadboard and Arduino microcontroller for measuring the temperature of the ice cubes in this study were prepared as suggested by Luthfi [11].

Table 2. The components required for setting up a temperature measurement system

Component	Quantity
DS18B20 sensor, 1 m	5
Terminal block, 3 pin	5
Breadboard, 830 holes	1
I2C LCD, 2×16	1
Jumper wire, 20 cm	As required
Jumper wire, 10 cm	As required
Resistor 4.7 kΩ	1
Arduino UNO DIP	1
USB Cable	1

2.3 Visualization

The temperature fields in the glass filled with water and ice cubes were visualized using HIKMICRO B20 thermal camera. The thermal camera has an infrared sensor resolution of 256×192 pixels, less than 40 mK thermal sensitivity, and a temperature range from -20 °C to 550 °C with 25 Hz frame rates. The thermal images can be recorded with an accuracy of ±2 °C and ±2 % for ambient temperatures 15 °C to 35 °C and object temperatures above 0 °C. The thermal camera uses a lens with a field of view, FOV of 37.2°×50°. The thermal camera setup used for this study and the typical image that can be taken using the thermal camera is shown in Fig. 2.

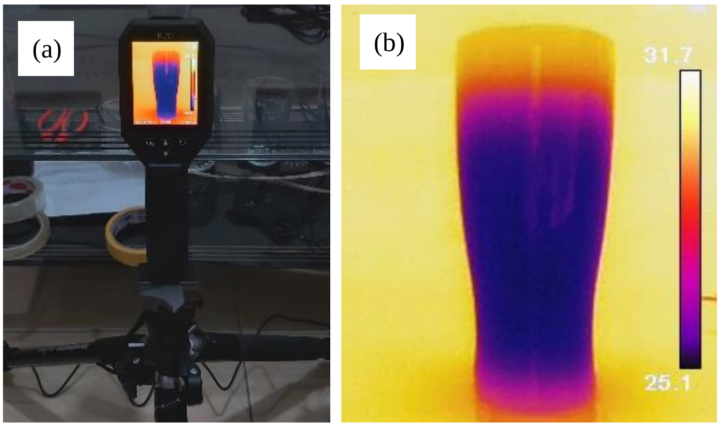


Fig. 2. Thermal imaging process (a) camera set-up (b) typical thermal image obtained in this study.

2.4 Supporting Tools and Equipment

There were four types of glass used for the experiment, glass A, B, C, and D (Fig. 3). Glass A was used for most of the time for performing ice cubes tests and comparison. Glass B, C, and D were used for investigating the effect of glass diameter only. The water level height was measured when all types of glasses were filled with 250 ml water. The average diameter of the glass can be calculated using the simple volume of cylinder formula (Table 3).

To ensure DS18B20 sensors are consistently placed at the same height among all glass used during the test, duct tape was used to attach the sensors securely on the glass. To avoid mistakes when placing the sensors on the glass, each sensor was marked using paper tape. A measuring glass was used to measure the correct and consistent amount of water poured into each glass during the tests.

The Arduino microcontroller was connected to a laptop, and it was run using Arduino application software and the temperatures were recorded into files. To ensure steady image recording, the thermal camera was fixed on a tripod and placed in front of the glass filled with water and ice cubes. The typical experimental set-up in this study is shown in Fig. 4 and all supporting tools and equipment used during the tests are listed in Table 4.

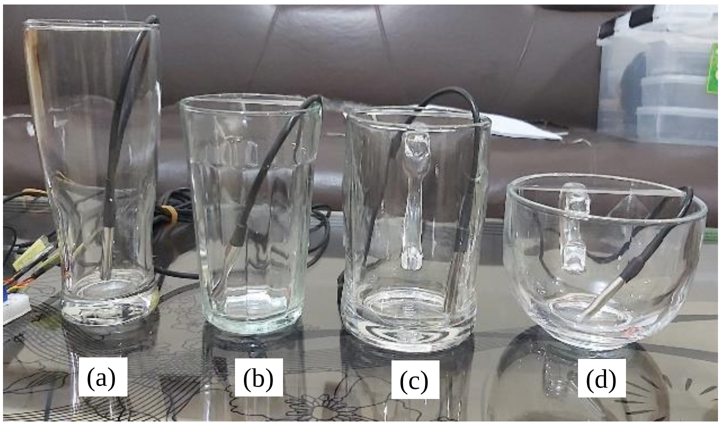


Fig. 3. The type of glass used for the tests (a) glass A, (b) glass B, (c) glass C, and (d) glass D.

Table 3. The water level and average diameter of glasses used for experiments when filled with 250 ml water.

Glass type	Water level (mm)	Average diameter (mm)
A	112	53
B	97	57
C	72	66
D	43	86

Fig. 4. Experimental set-up for testing the thermal performance of stainless-steel ice cubes.

Table 4. List of supporting equipment required

Item	Quantity
Glass A	4
Glass B	1
Glass C	1
Glass D	1
Measuring glass, 250 ml	1
Duct tape	As required
Paper tape	As required
Computer/Laptop	1
Tripod	1

2.5 Testing Procedure

After the Arduino-based temperature measurement system had been set up with all DS18B20 sensors placed properly in all glasses used for tests, the experimental set-up was tested and calibrated. The tests and calibration of the equipment were performed according to the procedure suggested by Luthfi [11].

The water inside the glass was not stirred during the tests. Thus, to produce a self-stirring effect and natural mixing inside the glass, ice cubes must place near the surface of the water inside the glass. Unlike water ice cubes, stainless-steel ice cubes naturally sink at the bottom of the glass, although it contains PCM inside them. Hence, the stainless-steel ice cubes were hung near the surface of the water.

The experiments were planned to be conducted in 4 series of tests in investigating the effect of ice cubes type, number of ice cubes, volume of water, and the diameter of the glass used. Each series used four glasses. The temperatures were recorded every 10 s and the thermal images were recorded when required. The ranges of parameters investigated for each series of tests are shown in Table 5.

Table 5. The range of investigated parameters

Test No	Specimen	Ice Cube Quantity	Volume of Water (ml)	Glass Type
1	Leeseph	2	250	A
	SSGP	2	250	A
	Remax	2	250	A
	Water	2	250	A
2	Leeseph	1	250	A
	Leeseph	2	250	A
	Leeseph	3	250	A
	Leeseph	4	250	A
3	Leeseph	1	150	A
	Leeseph	1	200	A
	Leeseph	1	250	A
	Leeseph	1	300	A
4	Leeseph	1	250	A
	Leeseph	1	250	B
	Leeseph	1	250	C
	Leeseph	1	250	D

3 Results and Discussion

3.1 Visualization of Temperature Field

The plots of transient development of temperature distribution in water inside the glass that contains Leeseph stainless-steel ice cubes are shown in Fig. 5. At the beginning when the ice cubes were initially placed inside the glass (Fig. 5(a)), the thermal image did not show a clear difference between the water and the ambient air. Some cold water starts accumulating at the bottom glass, but the coldest spot is around the upper middle part of the glass which might be the ice cubes that were hung around the surface of the water. There was a hot spot at the top of the glass which might occur due to fingers contact when setting up the thermocouple sensor. After 12–15 minutes of elapsed time (Fig. 5(b)–Fig. 5(c)), the difference between the water and the ambient air becomes more apparent. Cold water starts filling the glass, and the coldest spot has moved to the bottom. Although the cold spots are still visible at the location where the ice cubes were located, it becomes less distinctive. On the other hand, the hotspot at the top part of the glass becomes less visible and completely vanishes after 15 minutes. After 23 minutes, the cold spot where the ice cubes were located has completely disappeared. Most of the cold water has mixed well inside the glass with all parts of the glass clearly visible. At the end of the thermal image recording, after 66 minutes when the ice cubes were initially placed inside the glass (Fig. 5(f)), a clear difference between water and the ambient air can still be seen, although the water now becomes less cold compared to the previous thermal image. However, the glass now becomes colder and clearly visible compared to other images, and the surface of the table where the glass sits has even been affected by the cold water.

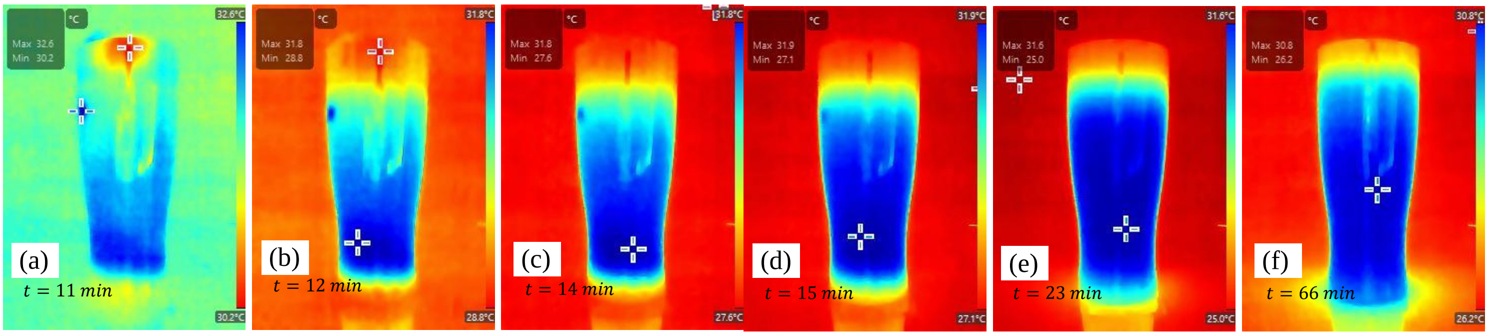


Fig. 5. Time development of temperature field around a glass filled with water and stainless-steel ice cubes.

3.2 Stainless-steel Ice Cubes Comparison

The transient temperature profiles of water containing various types of ice cubes are plotted in Fig. 6. Similar to Luthfi's finding in his paper [11], water ice cubes still produce the coldest minimum temperature of the water inside the glass which occurs at an earlier time compared to other ice cubes. However, Leeseph ice cubes in this study were found to perform almost as good as water ice cubes with comparable minimum water temperatures. The high price of SSGP and Remax stainless-steel ice cubes does not seem justifiable as the minimum temperatures from both ice cubes were found not as low and as the stainless-steel ice cubes from the cheaper brand, Leeseph. The stainless-steel ice cubes from the Remax brand are even worse. Having the highest price of IDR 15,500/piece, which is more than double that of Leeseph, the performance is the worst with the highest minimum temperature. The SSGP ice cubes on the other hand, although the minimum temperature is not as good as water and Leeseph ice cubes, can retain low temperatures longer than others. Further investigation of the thermal performance of all ice cubes using thermal images observation as shown in Fig. 7, found that after the cold water has mixed well, the glass containing SSGP ice cubes appears to have the coldest overall water temperature.

In order to reveal the actual thermal performance of each ice cube brand, the minimum water temperatures and the minimum duration to achieve those temperatures were extracted from Fig. 6 and plotted in Fig. 8. Fig. 8(a) confirms that water ice cubes produced the lowest minimum water temperature of 22.8 ºC. Followed by Leeseph and SSGP with minimum temperatures of 22.9 ºC and 23 ºC, respectively. As observed in Fig. 6, Remax stainless-steel ice cubes have the worst performance, with a minimum temperature of 23.7 ºC. The minimum time required to reach the minimum temperature as plotted in Fig. 8(b) shows an interesting trend. Water, Leeseph, and Remax ice cubes reach minimum temperatures at relatively short durations of 510 s, 570 s and 610 s, respectively. While SSGP ice cubes reach it at a relatively longer duration of 860 s and the temperature of the water remains lower than others afterward. This can be good or bad thermal performance, depending on what cooling conditions are required. If it is required a fast-cooling media that can reach the minimum temperature as fast as possible, water and Leeseph ice cubes are the best option. However, if retaining the lowest temperature as long as possible is required, then SSGP ice cubes are good alternatives.

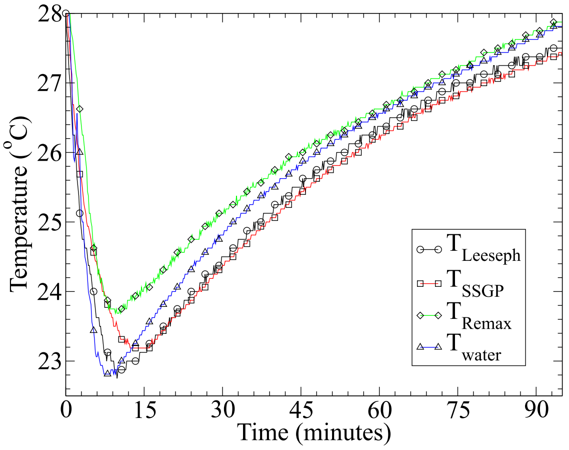
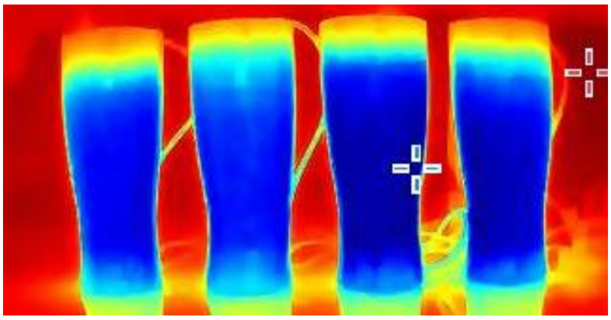


Fig. 6. The comparison of the time evolution of water temperature in glass A for different types of ice cubes used.



(a) (b) (c) (d)

Fig. 7. Temperature contour of stainless-steel ice cubes comparison (a) water ice cubes, (b) Remax, (c) SSGP, and (d) Leeseph.

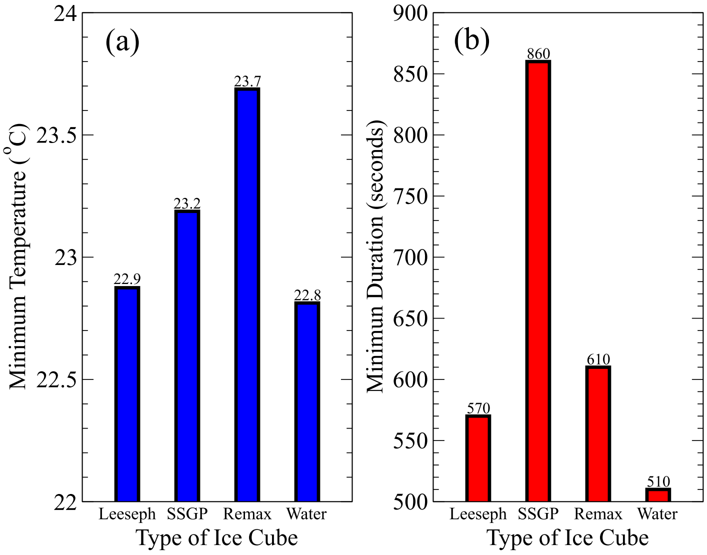


Fig. 8. The thermal performance of different types of ice cubes (a) minimum temperature and (b) minimum duration to reach minimum temperature.

3.3 Effect of the Number of Ice Cubes

The plot water temperature changes over time after Leeseph ice cubes were filled into four different glasses with various numbers of ice cubes used in each glass are shown in Fig. 9. It can be seen from the figure that the number of ice cubes used significantly affects the temperature of water in the glass. Each line in the figure shows a similar trend except for the ambient air temperature. The water temperature initially plunges to a minimum before slowly increasing and approaching ambient air temperature. The temperature of the glass that is filled with a larger number of ice cubes will decrease to a lower minimum temperature at longer time. As all temperatures increase at a similar trend, the water from the glass containing more ice cubes will have a lower final temperature at the end of the temperature recording.

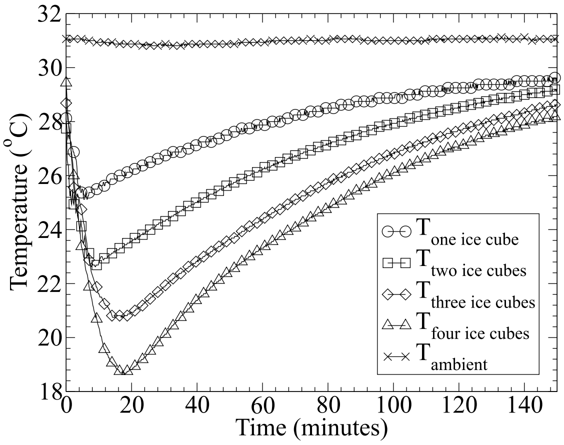
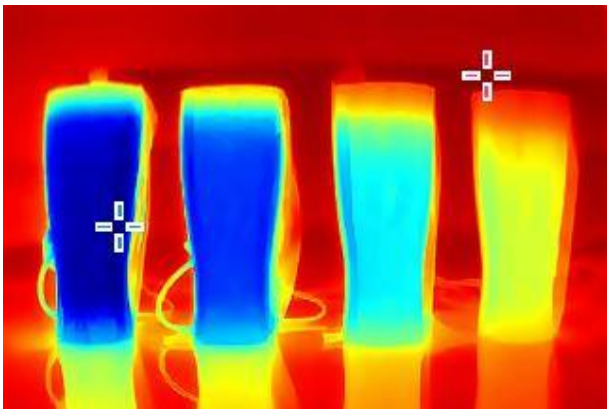


Fig. 9. Time evolution of water temperature in glass A for different quantities of stainless-steel ice cube used.

The temperature field of the water in each glass, as shown in Fig. 10, further confirms the effect of ice cube quantity on the overall temperature of the water. It is evident that the glass that has four ice cubes in it has the lowest overall temperature (Fig. 10(a)), while the one containing an ice cube only has the highest temperature (Fig. 10(d)). In order to obtain the trend of the effect of ice cube quantity, the minimum temperature data for each ice cube quantity used in Fig. 9 are collected and plotted separately in Fig. 11(a). As shown in the figure, the number of ice cubes used has a nonlinear relationship with the minimum water temperature. After conducting careful examination and performing curve-fitting by trial and error, it was found that the minimum temperature, T, can be best fit by applying power -1/5 to the data for the number of ice cubes used, N. Fig. 11(b) shows that by modifying the x-axis data into $N^{-1/5}$, the trend of the data become linear and can be well fitted using a linear regression line with an accuracy of $R^2 = 0.9991815$ and an Eq. 1.

$$T = 2.2295 + 22.939 \cdot N^{-\frac{1}{5}} \tag{1}$$



(a) (b) (c) (d)

Fig. 10. Temperature contour showing the effect of the number of ice cubes used (a) four ice cubes, (b) three ice cubes, (c) two ice cubes, and (d) one ice cube.

A similar procedure was applied to the minimum duration data in Fig. 9, and the results are plotted in Fig. 12(a). It is hard to tell what type of trend the minimum duration data can be fitted with. The easiest way and the highest probability of the trend line is a linear fit regression line (Fig. 12(b)) which result in a quite reasonable accuracy of $R^2 = 0.9963928$ by using an Eq. 2.

$$t = 135 + 236 \cdot N \tag{2}$$

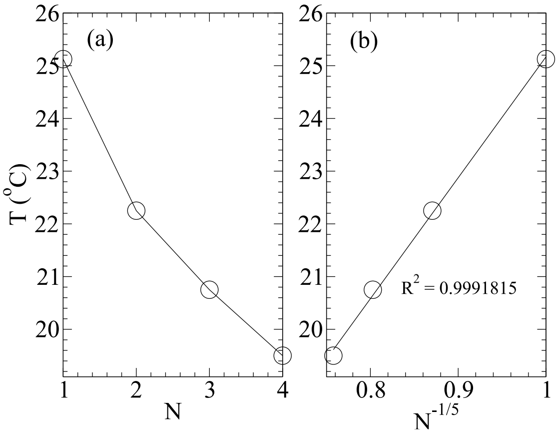


Fig. 11. The minimum temperature of water in glass A for different quantities of ice cubes used (a) raw data and (b) scaled data.

3.4 Effect of Volume of Water

The transient development of temperatures of four different volumes of water that were filled into four different glasses is plotted in Fig. 13. Each glass contained one Leeseph stainless-steel ice cube only. As can be seen in the figure, the effect of varying the volume of water used is similar to the effect of placing a different number of ice cubes in each glass. The glass that is filled with less amount of water was cooled to a lower minimum temperature compared to other glasses that have larger amounts of water. Although the volume variation will also affect the minimum duration as well as the ice cube number variation, here, the effect is less visible.

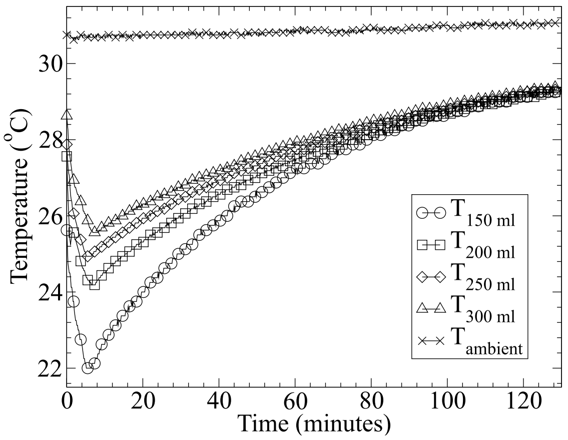


Fig. 13. Time evolution of water temperature in glass A for different volumes of water used.

The contour plot of the temperature field of all glasses used for the experiment, as shown in Fig. 14, further reveals the actual effect of the volume of water used. Although only one ice cube was filled into each glass, the figure shows that reducing the amount of water will significantly decrease the overall temperature of the water inside the glass. Similar to the effect of increasing the number of ice cubes used, a nonlinear trend is also observed for the effect of varying the volume of water used (Fig. 15(a)). By performing careful searching and testing by trial and error, it was found that the nonlinear trend can be best fitted with power 1/5. As can be seen in Fig. 15(b), modifying the x-axis into $V^{1/5}$ will make a smooth linear trend data that can be well fitted linear regression line having an accuracy of $R^2 = 0.9996158$ with an Eq. 3.

$$T = -1.7649 + 8.7349 \cdot V^{\frac{1}{5}} \qquad (3)$$

The data for the minimum time required to reach the minimum temperature that were taken from Fig. 13 are plotted in Fig. 16(a). Although previously the trend was not clearly visible, here it is evident that the minimum duration required increases linearly with the amount of water poured into the glass. The data for the time required are even so linear that the curve-fitting process using a linear regression line results in a perfect accuracy of $R^2 = 1$ with an Eq. 4.

$$t = 240 + 0.8 \cdot V \qquad (4)$$

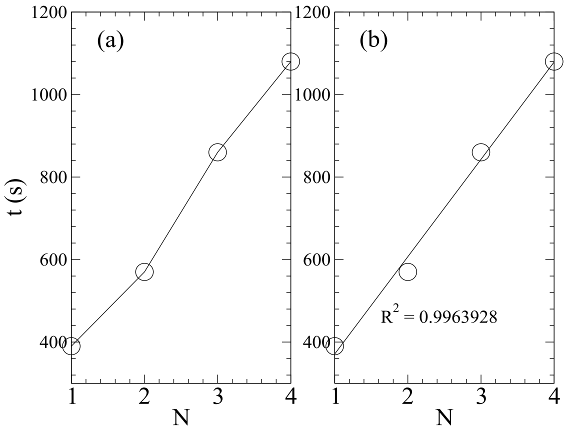


Fig. 12. The minimum duration to reach the minimum temperature of water in glass A for different quantities of ice cubes used (a) raw data and (b) scaled data.

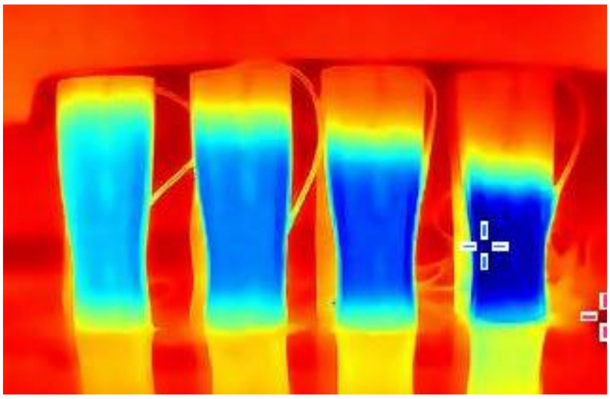

(a) (b) (c) (d)

Fig. 14. Temperature contour showing the effect of the volume of water in the glass (a) 300 ml, (b) 250 ml, (c) 200 ml, and (d) 150 ml.

3.5 Effect of Glass Average Diameter

The effect of using different glass diameters on the time evolution of water temperature in the glass is shown in Fig. 17. It can be seen from the figure that the diameter of the glass used for the experiment will affect the minimum temperatures of the water and the time required to reach them, although using the same amount of water and the same number of ice cubes. Overall, the temperature of the water inside glass type A, having a smaller diameter of 53 mm, is lower than those of glass type B or type C, with larger diameters of 57 mm and 66 mm, respectively. However, using glass type D, which has a significantly larger diameter than other glasses, 86 mm, does not increase the temperature of water further higher. On the contrary, the temperatures of water in glass D even drop significantly lower than the temperatures of water in other glasses. Careful examination of the thermocouple sensor set-up and temperature field of glass D from a thermal image taken during the test (Fig. 18) shows that the diameter was too large that the water level in glass D became so shallow that the sensor was too close to the ice cubes which may underestimate temperature reading. As the data from glass D may not be accurate, it will be excluded in further analysis of the curve-fitting process for minimum temperature and minimum time required.

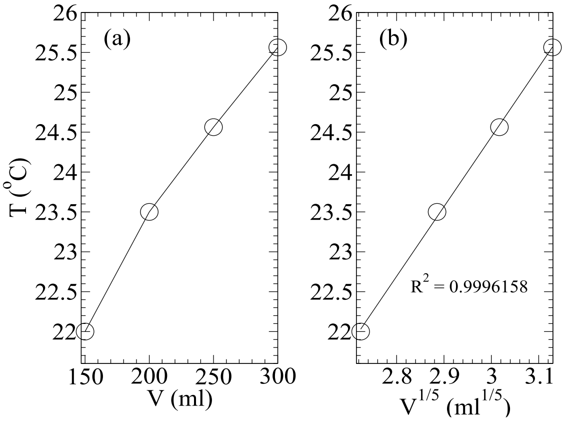


Fig. 15. The minimum temperature of water in glass A for different volumes of water used (a) raw data and (b) scaled data.

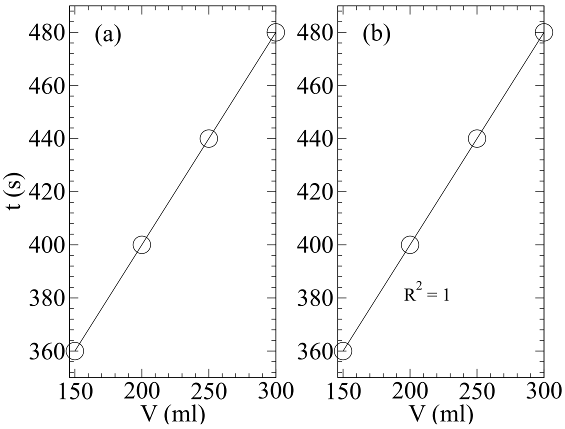


Fig. 16. The minimum duration to reach the minimum temperature of water in glass A for different volumes of water used (a) raw data and (b) scaled data.

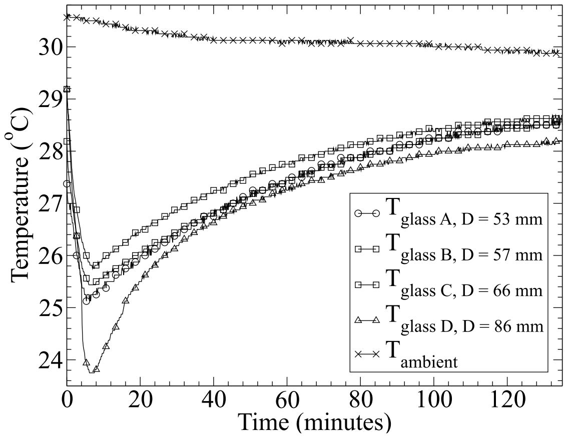
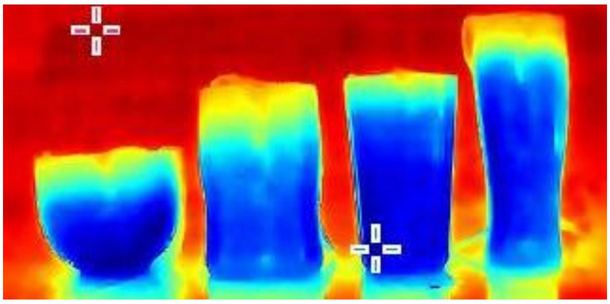


Fig. 17. Time evolution of water temperature for different types of glass used.



(a) (b) (c) (d)

Fig. 18. Temperature contour showing the effect of the average diameter of the glass (a) glass D, (b) glass C, (c) glass B, and (d) glass A.

Fig. 19(a) shows the minimum temperature data plotted against the diameter of the glass used for the experiment. Unlike the temperature data from the number of ice cube variations or data from changing volume of water, the data for the minimum temperature at different glass diameters appear to be linear. A linear regression line can almost perfectly fit the data with an accuracy of $R^2 = 0.9999991$ (Fig. 19(b)). The resulting linear regression equation from the curve-fitting process is Eq. 5.

$$T = 22.596 + 0.047435 \cdot D \tag{5}$$

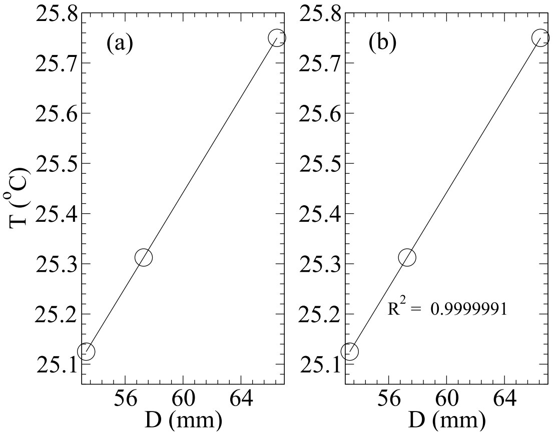


Fig. 19. The minimum temperature of water for different average diameters of glass used (a) raw data and (b) scaled data.

Similar to temperature data, the data for the minimum time required to reach the minimum temperature, as plotted in Fig. 20(a), also appear to be linear. This is not surprising as other minimum duration data from varying ice cube quantities or from altering the volume of water are also linear. As can be seen in Fig. 20(b), the linear regression line can fit the data well, having an accuracy of $R^2 = 0.9993698$ with an Eq. 6.

$$t = 20.194 + 6.7733 \cdot D \tag{6}$$

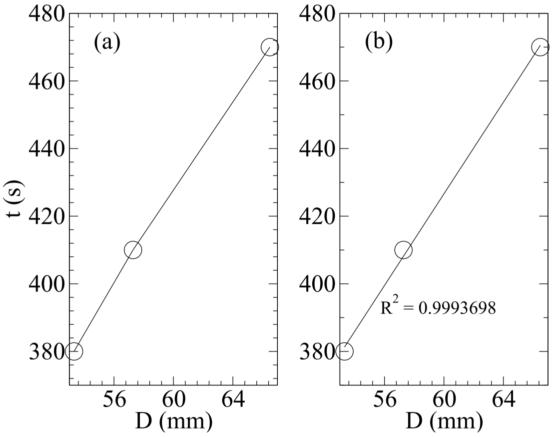


Fig. 20. The minimum duration to reach the minimum temperature of water for different average diameters of glass used (a) raw data and (b) scaled data.

3.6 Empirical Relationships

Eq. 1 – Eq. 6 are basically accurate enough in predicting the minimum temperature or the minimum time required, as the accuracy of all equations is greater than 0.9. However, it will not be practical to use the equation one by one when it is required to perform a lot of calculations. It would be more convenient to combine those equations into a single multipurpose equation than can predict the minimum temperature or the minimum time. To obtain such empirical equations, of course, requires more work to be done.

The first thing to do is to simplify the equations involved. The minimum temperatures are calculated from Eq. 1, Eq. 3, and Eq. 5, while the minimum time calculation use Eq. 2, Eq. 4, and Eq. 6.

All of these equations have a general form of $Y = a + bX^c$ with a, b, and c empirical constants that were obtained from experimental data. Constants a and b need to be adjusted and simplified so that all experimental data lie on the same regression line. The final form of the expected empirical equation is $Y = m + nX_{combined}$ with constant m and n obtained by manipulating and taking the average of constant a and b of the contributing equations. From Eq. 1, it was found that $T \sim N^{-1/5}$, from Eq. 3 $T \sim V^{1/5}$ and from Eq. 3 $T \sim D$. Hence by combining all contributing parameters it becomes $T \sim N^{-1/5}V^{1/5}D$. The curve-fitting process using linear regression line as shown in Fig. 21, fits well the data from all contributing parameters with an accuracy of $R^2 = 0.9995431$ and the final form of the empirical equation that incorporate all contributing parameters is Eq. 7.

$$T = 2.0945 + 0.0062456N^{-1/5}V^{1/5}D \qquad (7)$$

with $\boldsymbol{T}$ the minimum temperature in ºC, $\boldsymbol{N}$ number of ice cubes used, $\boldsymbol{V}$ volume of water in ml, and $\boldsymbol{D}$ diameter of the glass in mm.

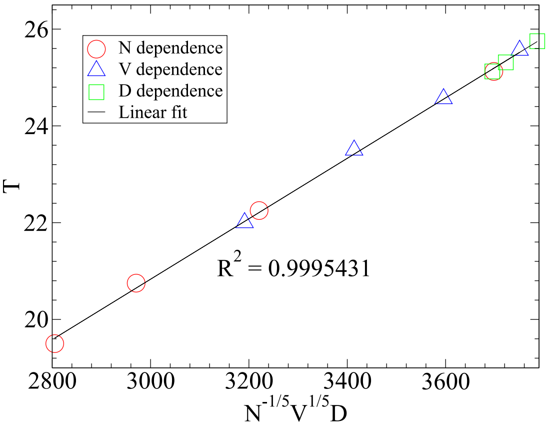


Fig. 21. The minimum temperature of water plotted against all contributing parameters combined.

The empirical equation for the minimum time required is easier to obtain as all contributing parameters in Eq. 2, Eq. 4, and Eq. 6 are linearly scaled with the minimum time, $t \sim N$, $t \sim V$ and $t \sim D$. Thus, all scaling relationships can be simply combined into $t \sim NVD$. The data from all contributing parameters plotted in Fig. 22 are well fitted with a linear regression line having an accuracy of $R^2 = 0.9995178$ with the final form of empirical relation that includes all contributing parameters (Eq. 8).

$$t = 151.96 + 0.018286\,NVD \qquad (8)$$

where $\boldsymbol{t}$ is the minimum time required in seconds.

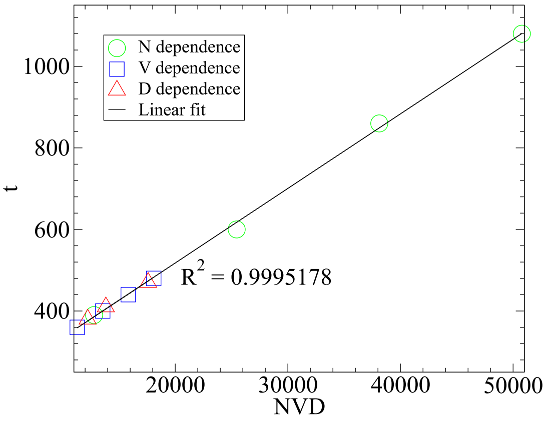


Fig. 22. The minimum duration to reach the minimum temperature of water plotted against all contributing parameters combined.

4 Conclusion

The thermal performance of stainless-steel ice cubes has been successfully investigated by using an Arduino microcontroller equipped with DS18B20 thermocouple sensors for the temperature measurement system and HIKMICRO B20 thermal images for visualizing the temperature field. Various brands of stainless-steel ice cubes have been tested and compared with water ice cubes. Leeseph brand stainless-steel ice cubes were found to have thermal performance almost as good as water ice cubes, while SSGP brand can retain lower water temperature longer than other brands including water ice cubes. The influence of the number of ice cubes used (N), the volume of water used (V) and the average glass diameter (D) has been studied, and empirical relations that can predict the minimum temperature and the minimum time required to cool the water using stainless-steel ice cubes have been established. The larger quantity of ice cubes used was found to lower the minimum temperature, $T \sim N^{-1/5}$ and to increase the minimum time, $t \sim N$. The more water used in the glass were observed to increase the minimum temperature, $T \sim V^{1/5}$ and to increase the minimum time, $t \sim V$. The larger average diameters of the glass used were found to increase both the minimum temperature, $T \sim D$ and the minimum time, $t \sim D$.

References

[1] N. J. Noor Izani, A. R. Zulaikha, M. R. Mohamad Noor, M. A. Amri, and N. A. Mahat, “Contamination of faecal coliforms in ice cubes sampled from food outlets in Kubang Kerian, Kelantan,” *Trop. Biomed.*, vol. 29, no. 1, pp. 71–76, 2012.

[2] V. C. Shruti, G. Kutralam-Muniasamy, F. Pérez-Guevara, P. D. Roy, and I. Elizalde-Martínez, “First evidence of microplastic contamination in ready-to-use packaged food ice cubes,” *Environ. Pollut.*, vol. 318, p. 120905, 2023, doi: https://doi.org/10.1016/j.envpol.2022.120905.

[3] J. Zou, L. Wang, and G. Sun, “Sustainable and Reusable Gelatin-Based Hydrogel ‘jelly Ice Cubes’ as Food Coolant. I: Feasibilities and Challenges,” *ACS Sustain. Chem. Eng.*, vol. 9, no. 46, pp. 15357–15364, 2021, doi: 10.1021/acssuschemeng.1c02853.

[4] J. Zou, L. Wang, and G. Sun, “Sustainable and Reusable Gelatin-Based Hydrogel ‘Jelly Ice Cubes’ as Food Coolant. II: Ideal Freeze-Thaw Conditions,” *ACS Sustain. Chem. Eng.*, vol. 9, no. 46, pp. 15365–15374, 2021, doi: 10.1021/acssuschemeng.1c06309.

[5] M. A. Ezan, E. Ozcan Doganay, F. E. Yavuz, and I. H. Tavman, “A numerical study on the usage of phase change material (PCM) to prolong compressor off period in a beverage cooler,” *Energy Convers. Manag.*, vol. 142, pp. 95–106, 2017, doi: 10.1016/j.enconman.2017.03.032.

[6] E. Oró, A. de Gracia, A. Castell, M. M. Farid, and L. F. Cabeza, “Review on phase change materials (PCMs) for cold thermal energy storage applications,” *Appl. Energy*, vol. 99, pp. 513–533, 2012, doi: 10.1016/j.apenergy.2012.03.058.

[7] J. Pereira da Cunha and P. Eames, “Thermal energy storage for low and medium temperature applications using phase change materials - A review,” *Appl. Energy*, vol. 177, pp. 227–238, 2016, doi: 10.1016/j.apenergy.2016.05.097.

[8] H. Selvnes, Y. Allouche, R. I. Manescu, and A. Hafner, “Review on cold thermal energy storage applied to refrigeration systems using phase change materials,” *Therm. Sci. Eng. Prog.*, vol. 22, no. December 2020, p. 100807, 2021, doi: 10.1016/j.tsep.2020.100807.

[9] G. M. Kumar, M. Mutharayappa, D. H. Rajappa, and B. A. Anand, “Reusable device for cooling beverages and liquid foods: A novel approach to replace ice in glass,” *J. Food Process Eng.*, p. e14074, 2022.

[10] Luthfi, Turmizi, Jefrizal, and R. Khairi, “Rancang Bangun Bahan Pengganti Es Batu Menggunakan Material Alternatif,” *Proceeding Semin. Nas. Politek. Negeri Lhokseumawe*, vol. 6, no. 1, pp. 65–69, 2022.

[11] Luthfi, “Analisis Termal Stainless Steel Ice Cubes dengan Menggunakan Sensor Termokopel Ds18b20 Berbasis Arduino,” *Teknologi*, vol. 23, no. 1, pp. 47–55, 2023, [Online]. Available: https://e-jurnal.pnl.ac.id/teknologi/article/view/3839

[12] A. N. Fathoni, N. Hudallah, R. D. M. Putri, K. Khotimah, T. Rijanto, and M. Ma’Arif, “Design Automatic Dispenser for Blind People based on Arduino Mega using DS18B20 Temperature Sensor,” *Proceeding - 2020 3rd Int. Conf. Vocat. Educ. Electr. Eng. Strength. Framew. Soc. 5.0 through Innov. Educ. Electr. Eng. Informatics Eng. ICVEE 2020*, pp. 0–4, 2020, doi: 10.1109/ICVEE50212.2020.9243254.

[13] W. Aritonang, I. A. Bangsa, and ..., “Implementasi Sensor Suhu DS18B20 dan Sensor Tekanan MPX5700AP menggunakan Mikrokontroller Arduino Pada Alat Pendeteksi Tingkat Stress,” *J. Ilm. Wahana ...*, vol. 7, no. 1, pp. 153–160, 2021, doi: 10.5281/zenodo.4541278.

[14] Ramesh Saha, S. Biswas, S. Sarmah, S. Karmakar, and P. Das, “A Working Prototype Using DS18B20 Temperature Sensor and Arduino for Health Monitoring,” *SN Comput. Sci.*, vol. 2, no. 1, pp. 1–21, 2021, doi: 10.1007/s42979-020-00434-2.