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Measurement of Specific Heat of Organic Materials Using Non-Isolating Container and Arduino

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Abstract: This study reports a novel method for specific heat measurements of organic materials namely potaoes, quinces and radishes. The method proposed in this work is novel in the sense that it employs a non-isolated container and an Arduino microprocessors. The actual measurements are simply managed by placing the organic materials within hot water in a non-isolating container and by monitoring the temperature and time by means of Arduino UNO microprocessor. The heat leakage due to the non-isolated container is determined by using the heat versus time graph of the system and by mathematically modeling the temperature decrease by the time due to the heat exchange between the hot water and the environment. The measurements have revealed that the relative errors for the measurements are approximately % 4.75 for potatoes, % 21.50 for radishes and % 1.30 for quinces. The approach described in this work is inexpensive, very easy to apply and can potentially be beneficial for basic physics, science and engineering research activities.

Keyword : Specific heat, Specific Heat Measurement, Arduino, Potatoes, Radishes, Quinces.

1. Introduction

Physics deals with the natural phenomena involving energy or matter and resolves the concepts and natural laws, develops theories that can predict the results of experiments. (Sears et al., 1974; Serway and Jewett, 2018) Physics is naturally considered to be reasonably challenging for majority of the students due to high involvement of abstract and complicated concepts, conceptual interrelatios and due to lack of convincing concrete experiments. (Fishbane et al., 2003; Prensky, 2005; Veloo et al., 2015; Vilia & Candeias, 2020) Physics education research, on the other hand, aims to identify the subjects that students have severe difficulties in learning and understanding and accordingly to raise individuals with the competencies required by the society by eliminating learning and comprehension difficulties. For this reason, it is important to tackle difficult-to-understand subjects in physics with simple and innovative teaching materials, methods and approaches (Wieman & Perkins, 2005; Lewis and Linn, 1994; Marioni, 1989).

One of the subjects that students have difficulties in learning within the scope of physics courses is thermodynamics which mainly deals with heat energy and temperature, energy conservation and energy transformations within the physical systems. (Sözbilir, 2003) The basic concepts of thermodynamics namely heat, temperature, thermodynamic work, energy and the relationships between them are amongst the most fundamental topics of physics. A brief scrutinizing the relating literature points out that most students have misconceptions concerning subjects such as heat, temperature, internal energy and specific heat. (Barrow 1988; Lewis & Linn, 1994; Viennot, 1998; Alwan, 2011) It is surely important to provide students an education atmosphere full of collaborative learning methods, discussions and indeed experimentations to overcome and improve students' skills in laboratory applications (Deslauriers et al., 2011).

Specific heat and heat capacity are fundamental and very important concepts for both scientifically, and technologically. Specific heat is a measure of heat energy of a substance and described as the heat energy change per unit temperature change of per unit mass of the substance. Therefore, the greater the specific heat of a substance, the more heat energy per unit mass is necessary to increase the temperature by 1 K. (Kittel, 2004) Thermal energy or the heat energy is, on the other hand, equivalent to the internal energy or overall micro mechanical energy of the particles of the substance, hence it has primary importance both scientifically and technologically and consequently educationally. Determination of specific heat concerning food science is also important in terms of estimating the amount of calorie within the food substance. (Hwang & Hayakawa, 1979; Chen, 1985) Relating literature review points out that studies have been conducted on the specific heat measurements especially on exotic fruits such as mulberry, cashew apple, cocoa, kiwi, pitanga, soursop fruit and also other fruits like yellow melon, tomato, bael fruit, oil palm fruit. (Sonawane et al., 2020; Aghbashlo et al., 2008; Oliveira et al., 2012) It is obvious that there are studies on specific heat measurements concerning food science however there are no measurement studies in the literature on organic materials such as radishes, potatoes, quinces.

It is the conventional practice of physics that the specific heat of a substance is measured by using an isolated container named as calorimeter by immersing the actual substance into the water. (Lohajinda et al., 2019) However, the conventional approach has been problematic due to uncontrollable heat leakage to the environment. Therefore it is highly desirable to develop an alternative procedure to measure the specific heat or heat capacity that eliminating the heat leakage for both scientifically and educationally.

In addition, if the approach employs basic and non-expensive equipment namely an ordinary non-isolated container and an Arduino microprocessor it would be very beneficial. Arduino microprocessors are electronic devices that includes digital and analog sensors, LEDs, motors and heating elements, where sensors and transducers and can be programmed with C language and applications can be easily realized. Arduino microcontrollers can collect data from various sensors with the help of these electronic devices, where very good work can be done with the introduction of robotic coding. (Galeriu et al., 2014; Petry et al., 2016) The importance of the studies using Arduino in science, physics and physics education is increasing because the microprocessor is cheap, the programming language is easy and understandable and it has also an open source. For this reason, measurement tools and experimental setups can be designed with the Arduino Uno microcontroller and used in physics experiments (Organtini, 2018).

The aim of this study is to experimentally and theoretically analyze the concepts of specific heat of organic materials alternatively using Arduino Uno with a procedure that employs a non-isolated container and mathematical modeling. The procedure is employed to measure the specific heats of some specific organic materials, namely potatoes, quinces and radishes.

2. Theory of Specific Heat

Heat capacity, a property of matter, can be defined as the amount of heat given to or obtained from a substance in order to change the temperature of the substance 1 Celsius or 1 Kelvin. Therefore, the heat capacity of an object, denoted by C, is given by,

$$C = \frac{dQ}{dT} \tag{1}$$

where dQ is the amount of heat that must be added or removed from the substance to raise the temperature by dT. The amount of heat given to the system is obviously accommodated within the substance and is determined by the microscopic properties of the substance, such as the micro mechanical energy of the constituent particles and chemical bond energies of the particles. Therefore, the measurement of heat capacity is important to specify numerous physical and chemical properties of the substance. Correspondingly, specific heat of a substance is defined as the amount of heat added to or removed from the substance per unit mass and per unit temperature change of the substance.

$$c = \frac{1}{m}\frac{dQ}{dT} \tag{2}$$

Accordingly, the specific heat of a substance is defined as the heat capacity per unit mass of the substance. The specific heat capacity of a substance, usually denoted by c, is the heat capacity (C) of a substance divided by the mass (m) of the substance.

Heat capacity and likewise the specific heat of a substance is due to the motion of the constituent particles which are, regarding the solid substances, bound with each other by chemical bonds and relentlessly vibrate around an equilibrium position. Theoretical resolution of heat capacity was a bit of problem of classical physics however tackled and resolved by Einstein who treated the particles of the solid as non-interacting quantum harmonic oscillators vibrating with fixed frequencies. Einstein model of heat capacity resolved the main problem, which is the decrease of the heat capacity as the temperature decreases, nevertheless was unable to explain the whole temperature range from absolute zero to room temperatures. The problem was later tackled by Debye by assuming the particles vibrating with different frequencies ranging from 0 to a maximum frequency of v_m. Accordingly, the mean internal energy (U) which is equal to the heat energy (Q) of a single vibrating oscillator (particle) can be calculated from,

$$Q = \frac{9h^4}{k^3 T_D^3} \int_0^{v_m} \left(\frac{1}{2} + \frac{1}{e^{\frac{hv}{kT}} - 1} \right) v^3 dv \tag{3}$$

Where $T_D = \frac{hv_m}{T}$ denotes the Debye temperature of the solid, h is the Planck's' constant, k denotes the Boltzmann's' constant, v denotes the frequency and T denotes the absolute temperature of the substance. Accordingly the heat capacity of the substance, which accommodates overall N particles, can be calculated by using the definition of (1) and by taking the first derivative of the internal energy (heat energy) with respect to temperature, which yields,

$$C = 9Nk \left(\frac{T}{T_D} \right)^3 \int_0^{T_D/T} \frac{X^4 e^x}{(e^x - 1)^2} dx \tag{4}$$

where $x = \frac{hv}{kT}$ denotes the energy, quanta divided by thermal energy of a particle. This final expression can be approximated for high and low temperatures with respect to Debye temperature of the solid. At high temperatures if the condition of $\frac{T}{T_D} \gg 1$ holds then it means $x = \frac{hv}{kT} \ll 1$ which leads to the simple result of,

$$C = 3\ Nk \tag{5}$$

which is known as Dulong-Petit law. The Dulong-Petit law expresses that at room temperatures and above the specific heat of solid substance is approximately equal to,

$$c = \frac{3Nk}{m} \tag{6}$$

which is obviously constant. The specific heat at about room temperature accordingly depends on the number of oscillators or vibrating particles within the solid substance, N. The quantum mechanical calculation outlined above can be specified for any substance by taking into account certain substance parameters such as the mass of the particles, m_0, and energy of the chemical bond. Therefore, it is legitimate to express the mass of the substance, m, in terms of the mass of oscillating atoms or molecules,

$$m = N\ m_0 \tag{7}$$

where m_0 denotes the mass of the oscillating particle and N denotes the total number of particles within the substance. In this case the specific heat of any substance can be given by,

$$c = \frac{3k}{m_0} \tag{8}$$

This expression defines the specific heat of any solid-state substance in terms of the mass of a single oscillating particle, m_0.

3. Method

3.1. Experimental Setup

The aim of the study is to determine the specific heat of certain organic materials, namely potatoes, radishes and quinces. The experimental set up mainly consists of an ordinary computer with appropriate code loaded, an ordinary kettle, a precision scale, a digital thermometer, a Styrofoam container, a scaled container, an Arduino Uno microprocessor, one DS18B20 water proof temperature sensor, a breadboard, an Arduino Uno-computer communication cable and connecting cables. The experimental set up containing all the equipment is shown in figure 1.

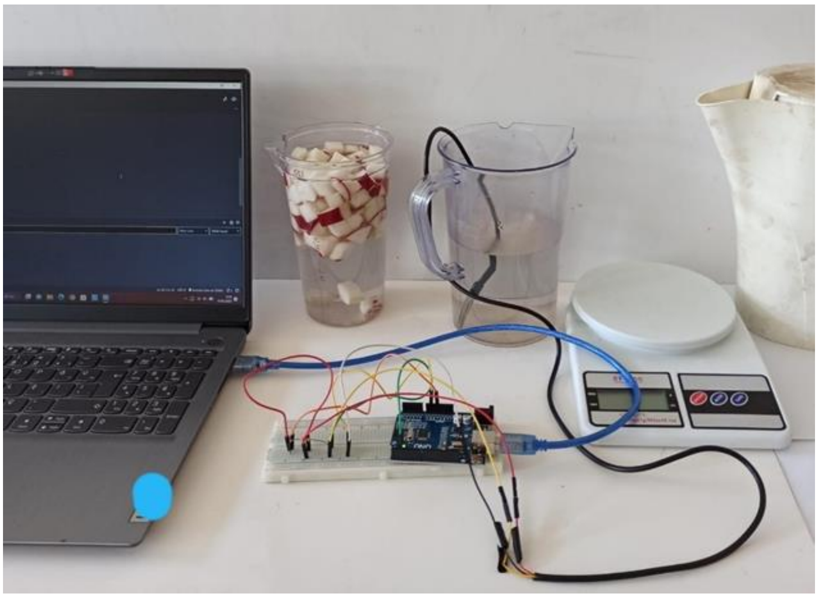

Figure 1. The photography of experimental setup showing all parts of the equipment used to carry out the measurements.

The actual connections between the DS18B20 temperature sensor and the arduino Uno is shown in the figure 2. The DS18B20 temperature sensor is in a waterproof cover and it sends 9 or 12-bit digital output via onewire protocol. The DS18B20 temperature sensor measures temperatures from -55°C to +125°C and converts 12-bit temperature to digital word in 750 ms.

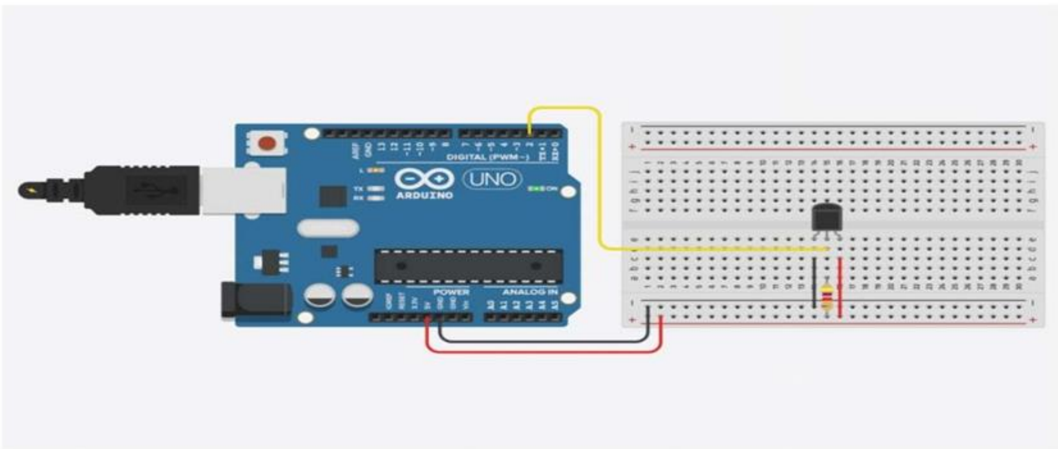

Figure 2. The connections and wiring of the temperature sensor and the Arduino Uno.

3.2. Arduino Uno and the Temperature Sensor

The Arduino Nano microprocessor can obviously be used for countless applications by an appropriate code. The code is obtained from the Arduino Library specifically prepared for the DS18B20 temperature sensor. The photography of the actual wiring between the DS18B20 temperature sensor, the computer and Arduino Uno is shown in the figure 3.

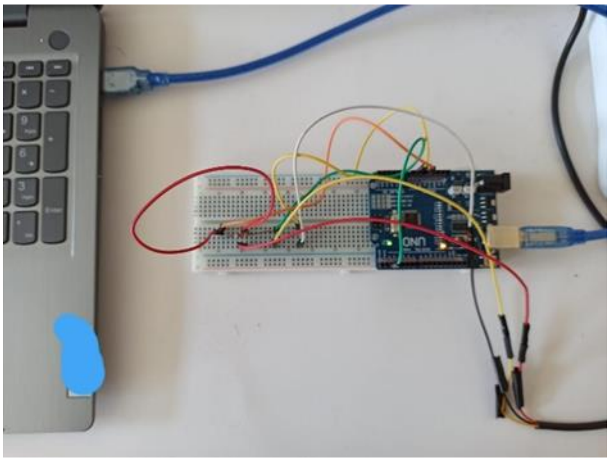

Figure 3. The photography of the actual wiring of Arduino Uno, the temperature sensor and the computer.

3.3. Novel Specific Heat Analyses Procedure

The experimental procedure employed in this work is a novel one and based on eliminating the heat leakage to the environment by taking the advantage of the Arduino Uno systems and the temperature sensor. The experimental procedure is based on heat energy transfer between cold and hot substances until the thermal equilibrium reached and extracting the actual heat loss to the environment other than the actual material. In order to eliminate the heat leakage of the Styrofoam container, the container is filled with hot water (approximately 80 C) and the gradual decrease of the temperature of the water is monitored by the Arduino Uno as a function of time, specifically the temperature is measured every 10 seconds or 5 seconds. This gradual decrease before immersing the actual material is then mathematically modeled as , $\mathrm{T} = A - Bt$,by estimating the slope of the decrease, that is, $B = \frac{dT}{dt}$. Experimentally determined slope or B obviously gives the heat energy leakage to the environment from the Styrofoam and water system. At the Arduino Uno treads the temperature the material, whose initial temperature is well known, is suddenly and carefully immersed within the hot water and let the system read the temperature as a function of time. Obviously immediately heat exchange between the hot water and the cold material occurs and a thermal equilibrium must be reached within a short time depending on the mass of the material. If the thermal equilibrium temperature is read as T_{E} then real equilibrium temperature for the material must be higher than the determined T_{E} due to the continuous heat leakage to the environment. Consequently, the real temperature can be given by,

$$T_R = T_E + \left(\frac{dT}{dt}\right)\Delta t \tag{9}$$

The specific heat can experimentally be determined in accordance with,

$$c_m = \frac{m_w c_w (T_{wi} - T_R)}{m_m (T_R - T_{mi})} \tag{10}$$

where m_w denotes the mass of the water, c_w is the specific heat of water which is 4.18 J /g C, T_{wi} denotes the initial temperature of water, T_E denotes the equilibrium temperature of water, m_m is the mass of the material, T_R denotes the real equilibrium temperature which is corrected in terms of heat leakage to the environment and finally T_{mi} denotes the initial temperature of the material before immersing in the hot water.

4. Results and Data Analysis

4.1. Measurements for Potatoes

The experimental sequence detailed before is applied to the potatoes and water system and the temperature is plotted as a function of time in the figure 4, based on the data obtained by the temperature sensor and the Arduino-computer system. The temperature data, in this case, is collected by the Arduino-sensor system every 30 seconds.

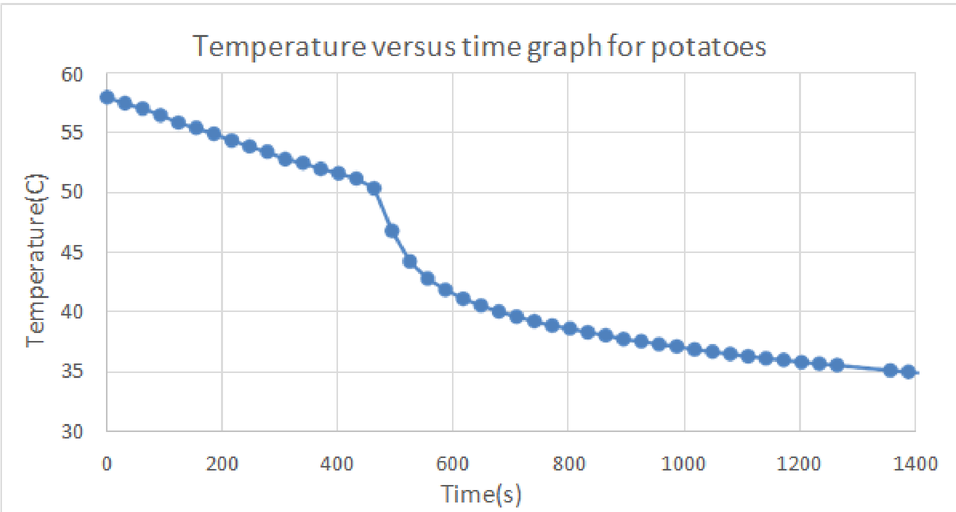

Figure 4. Temperature plotted as a function of time for potatoes, showing a clear sharp decrease due to the heat transfer from hot water to cold potatoes sampling.

It is clear from the figure that the instantaneous temperature at which the potatoes are immersed within the hot water is T_i = 50.38 C , which is the initial temperature of water, and at an instant of t_i = 462.35 s. The initial water of the potatoes is separately determined and measured by a digital thermometer as T_{ip} = 18.00 C. The crucial stage of the approach is the determination of the equilibrium temperature of the water-potatoes system. This is managed by determining reading the temperature at which the heat transfer from the hot water to the potatoes is terminated. This temperature can be determined by estimating the starting point of the linear relation between the temperature- time relations at the end of the sharp decrease of the temperature. The equilibrium is reached at a temperature of T_e = 37.75 C at an instant of t_f = 893.07 s.

In order to eliminate the actual heat leakage from the hot water container system to the environment one ought to mathematically model the linear decrease of temperature as a function of time. This can be achieved by only taking the first linear part of the graph, that is between the temperatures of 58.00 C and 51.19 C, before the potatoes sampling is immersed to the hot water. The Graph employed to eliminate the heat leakage is shown in figure 5.

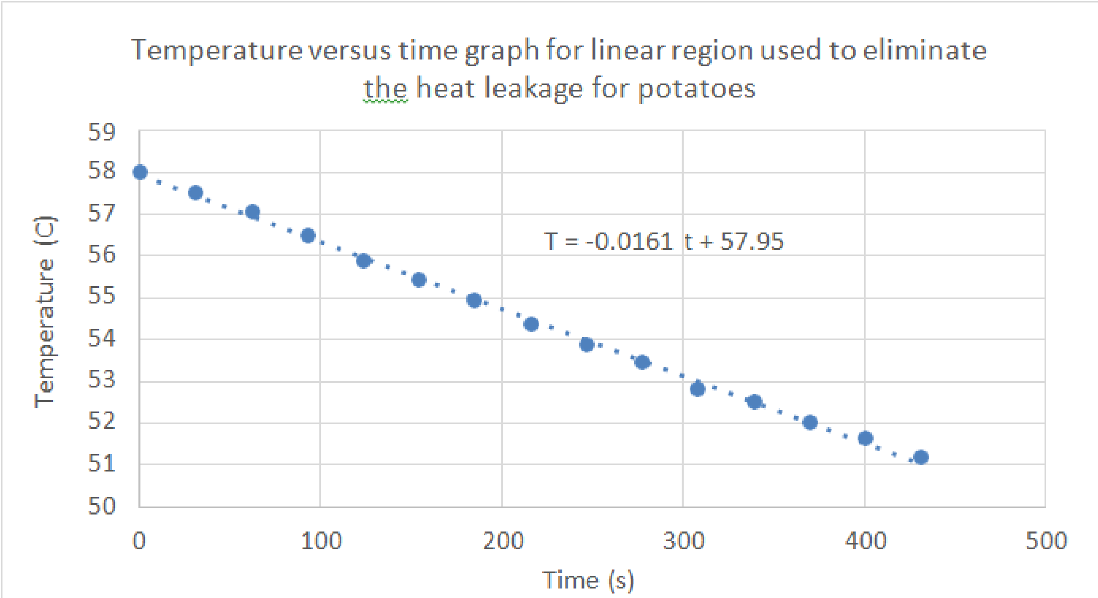

Figure 5. Time-dependent temperature graph for potatoes between the temperatures of 58.00 C and 51.19$°C$. The gradual decrease is curve fitted and mathematical modelling is found as T = -0.0161 t + 57.95.

It is now clear from the figure 5 that the slope of the gradual decrease of temperature, which gives the heat leakage for the hot water-container system, is determined as $\frac{dT}{dt} =$ 0.0161 based on the equation of T = -0.0161 t + 57.95. It is also possible to determine the time interval of heat transfer from the hot water and the potatoes sampling which can directly be read from the graph as Δt = 893.07s − 462.35s = 430.72 s. Accordingly, the real equilibrium temperature can be calculated as T_R = 37.75 + 0,0161 (430.72) = 44. 69 °. m_w = 1000.0g m_q = 248.0g The specific heat for potatoes can now be calculated by the equation given previously as, $c_p = \frac{1000.1.(50.38-44.69)}{248.(44.69-18.00)} = 0.8596\,\frac{cal}{gC}$. The relative error for the measurement can be estimated as $E_R = \frac{0.8596-0.8206}{0.8206} = 4.75$, which means % 4.75 which is surely highly acceptable.

4.2. Measurements for Radishes

The experimental structure applied to the radishes-water system and the temperature is plotted as a function of time in the figure 6.

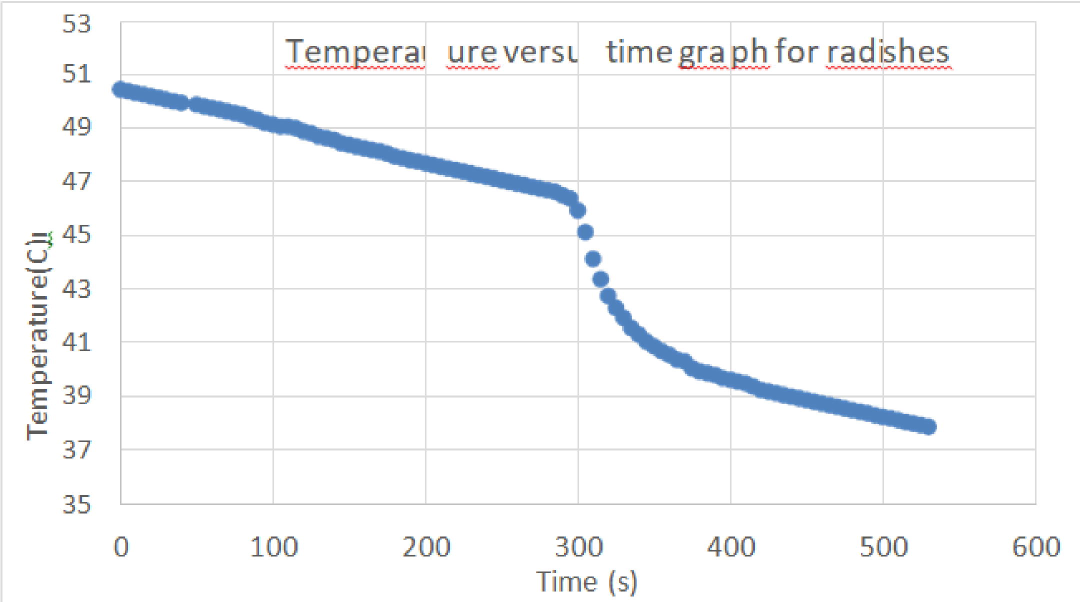

Figure 6. Temperature plotted as a function of time for radishes, showing a clear sharp decrease due to the heat transfer from hot water to cold radishes sampling.

The figure clearly shows that the temperature at which the radishes that are dipped within the hot water is T_{iw} = 46.38 C, and the instantaneous time is approximately is t_i = 295.00 . The initial temperature of the radishes is separately determined and measured by a digital thermometer as T_{ir} = 22.00 C. The crucial stage of the methodology is the determination of the real equilibrium temperature of the water-radishes system by eliminating the heat leakage to the environment. This is achieved by reading the temperature at which the heat transfer from the hot water to the potatoes is terminated. This temperature can be determined by approximating the beginning point of the linear relation between the temperature-time at the termination of the sharp decrease of the temperature. The graph reveals that the equilibrium is reached at a temperature of T_e = 40.06 C at an instant of t_f = 375.00 s.

In order to remove the actual heat leakage from the hot water-container system one ought to mathematically model the linear reduction of the temperature as a function of time. This can be succeeded by only taking the first linear part of the graph that is between the temperatures of 50.44 C and 46.50 C, before the radishes sampling is immersed within the hot water. The graph employed to eliminate the heat leakage is shown in figure 7.

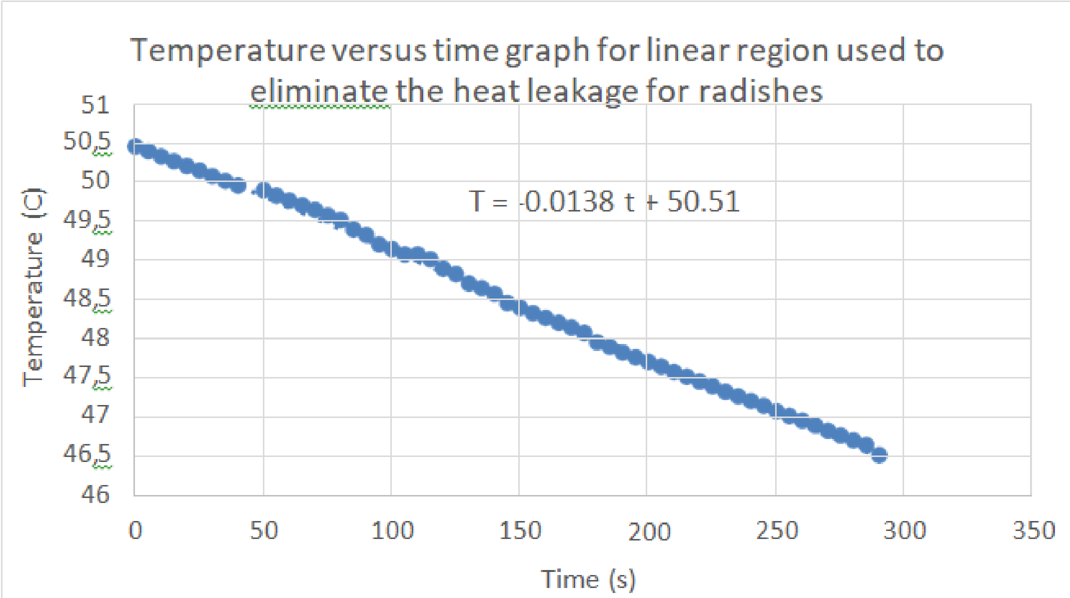

Figure 7. Time-dependent temperature graph for radishes between the temperatures of 50.44 $°C$ and 46.50$°C$. The gradual decrease is curve fitted and mathematical modelling is found as T = -0.0138 t + 50.51.

The figure 7 clearly demonstrates that the slope of the gradual decrease of the temperature, which provides the heat leakage for the hot water-container system, is determined as $\frac{dT}{dt}$ = 0.0138 based on the equation of T = -0.0138 t + 50.51. It is also possible to determine the time interval of the heat transfer from the hot water and the radishes sampling which can directly be measured from the graph as $\Delta t = 375.00s - 295.00s = 80.00\ s$. Consequently, the real equilibrium temperature can be calculated as T_R = 40.06 + 0,0138 (80.00) = 41.16°. In order to determine the masses of the water and the radishes, numerous measurements are carried out and the average masses are found to be, m_w = 590.0g, m_q = 212.0g. The specific heat for radishes can now be calculated by the equation given previously as, $c_p = \frac{590\ 1\ (46.38-41.16)}{212\ (41.16-22.00)} = 0.7580\,\frac{cal}{gC}$. The relative error for this measurement can be estimated as $E_R = \frac{0.966-0.7580}{0.966} = 21.50$, which mean % 21.50 which is acceptable within the limits of experimental equipment.

4.3. Measurements for Quinces

Time dependence of the temperature for quinces-water system is plotted in figure 8. This time data is collected by the Arduino every 5 seconds and a clear sudden decrease is detected when the quinces are released within the hot water. It is easy to read the initial temperature of the water and the time instant of that initial temperature of the system. Initial temperature of the water is read as T_{iw} = 51.44 C and the time is read as t_i = 305 s. The initial temperature of the quinces is separately determined and measured by a digital thermometer as T_{ir} = 21.00 C. The crucial stage of the approach is the determination of the equilibrium temperature of the water- quinces system. This is managed by determining reading the temperature at which the heat transfer from the hot water to the quinces is terminated. This temperature can be determined by estimating the starting point of the linear relation between the temperature-time relations at the end of the sharp decrease of the temperature. The equilibrium is reached at a temperature of T_e = 40.69 C at an instant of t_{ff} = 465.00 s.

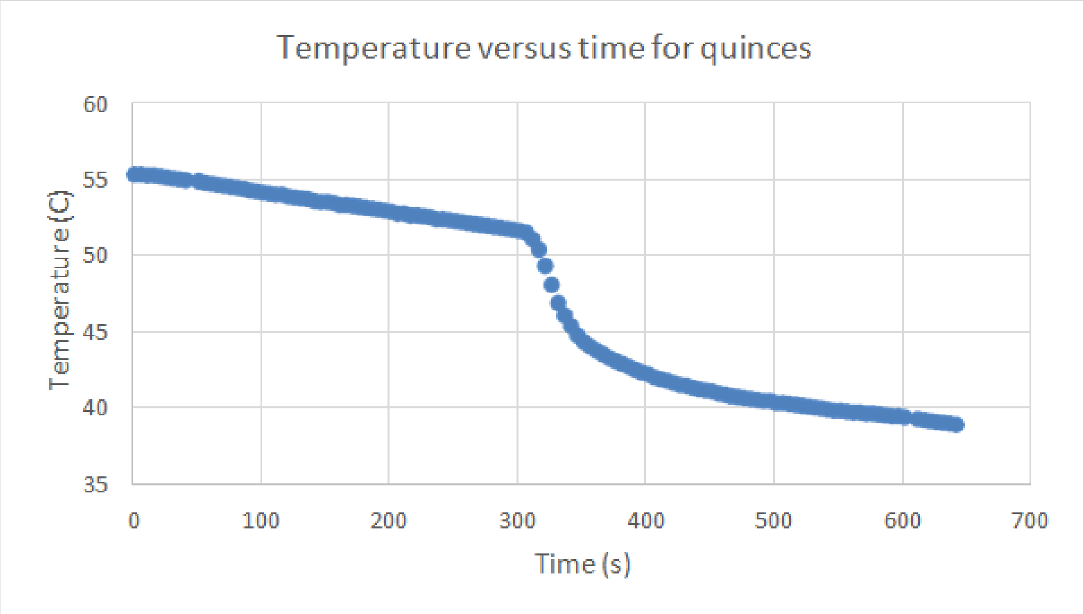

Figure 8. Temperature plotted as a function of time for quinces, showing a clear sharp decrease due to the heat transfer from hot water to cold potatoes sampling.

In order to eliminate the actual heat leakage from the hot water container system to the environment one ought to mathematically model the linear decrease of temperature as a function of time. This can be achieved by only taking the first linear part of the graph that is between the temperatures of 55.25 C and 51.50 C, before the quinces sampling is immersed to the hot water. The Graph employed to eliminate the heat leakage is shown in figure 9.

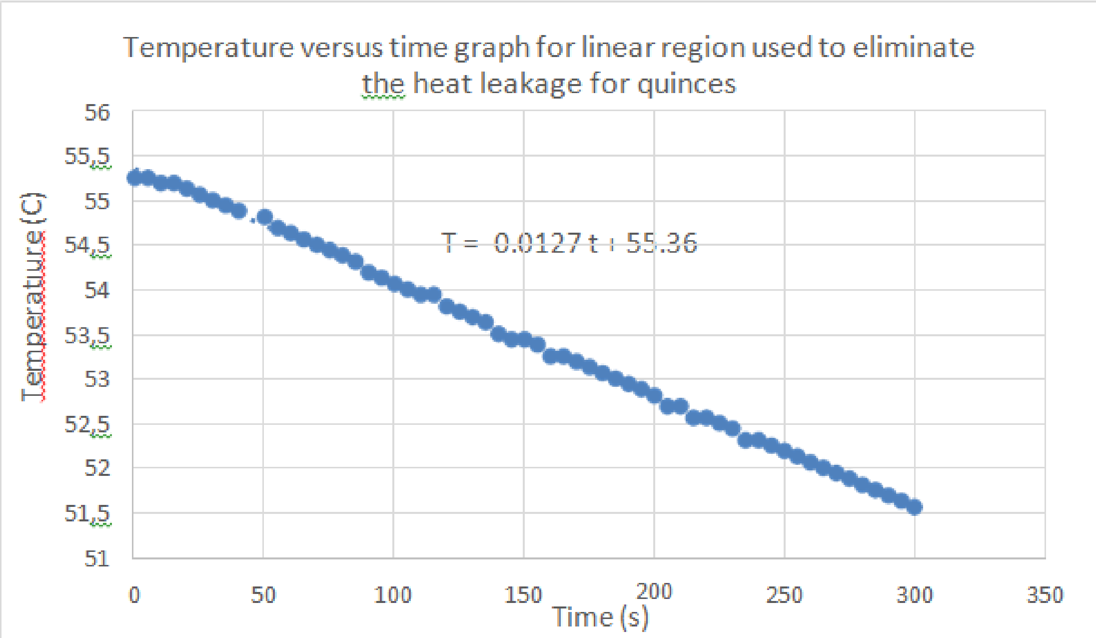

Figure 9. Time-dependent temperature graph for quinces between the temperatures of $55.25\ °C$ and $51.50\ °C$. The gradual decrease is curve fitted and mathematical modelling is found as T = -0.0127 t + 55.36.

It is now clear from the figure 9 that the slope of the gradual decrease of temperature, which gives the heat leakage for the hot water-container system, is determined as $\frac{dT}{dt} =$ 0.0127 based on the equation of T = -0.0127 t + 55.36. It is also possible to determine the time interval of heat transfer from the hot water and the quinces sampling which can directly be read from the graph as $\Delta t = 465.00s - 305.00s = 160.00\ s$. Accordingly, the real equilibrium temperature can be calculated as $TR = 40.69 + 0.0127\ (160.00) = 42.72$ $°C$. The masses of the water and quinces are measured several times and the average values are given as m_w = 569.0 g m_q = 256.0 g, respectively. The specific heat for quinces can now be calculated by the equation given previously as, $c_p = \frac{569\ 1\ (51.44-42.72)}{256\ (42.72-21.00)} = 0.8920\ \frac{cal}{gC}$. The relative error for the measurement can be estimated as $E_R = \frac{0.8920-0.8804}{0.8920} = 1.30$, which means % 1.30 which is perfect.

5. Conclusions

The present work has reported the specific heat measurements of organic materials, namely potatoes, quinces and radishes by means of a novel method and inexpensive equipment. The proposed approach in this work is original due to employing a non-isolated container and an Arduino microprocessor. The data collections are simply accomplished by insertion the organic substances within the hot water and by monitoring the temperature and time variables by means of Arduino UNO microprocessor. The approach is mainly based on elimination of heat leakage to the environment since the no isolating container is employed. The heat leakage to the environment due to the non- isolated container is determined by using the heat versus time graph and by mathematically modeling the temperature decrease by the time. The experimental efforts have exposed that the relative errors for the measurements are % 4.75 for potatoes, % 21.50 for radishes and % 1.30 for quinces. This simple approach is surely inexpensive, very easy to apply and can potentially be employed for basic physics, science and engineering research undertakings and also for teaching undertakings.

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