Vol. 12, No. 1 (2023) : 118 - 128
DOI : http://dx.doi.org/10.23960/jtep-l.v12i1.118-128

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

Arduino-Based Data Acquisition Device Design for Specific Heat Determination of Hot Vegetable Oil

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Article History :

Received : 21 September 2022
Received in revised form : 15 November 2022
Accepted : 19 December 2022

Keywords :
ATmega2560,
DAQ,
Heat capacity,
Hysteresis,
Vegetable oil

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ABSTRACT

Vegetable oil is commonly used for cooking and frying at high temperatures. Information on the oil's specific heat in a process can help estimate the time and energy spent to reach a particular temperature. However, finding an accurate and affordable instrument for measuring specific heat at high temperatures was complex. This study aimed to design a prototype data acquisition device (DAQ) that can support the specific heat of high-temperature vegetable oil determination using the Joule experiment and Newton's correction. This study had two stages: prototype design/construction and prototype testing. The DAQ prototype consisted of a PZEM-003 power sensor, a PT100 temperature sensor, a relay, and an Arduino Mega 2560. The measurement results were displayed on an LCD and recorded in Microsoft data streamer. The prototype was tested by comparing the temperature, voltage, and current with commercial instruments resulting in accuracy and precision of 99.97% (99.95%), 99.97% (99.86%), and 99.99% (99.86 %), respectively. Performance tests showed that the specific heats of canola, corn, and sunflower oils at 100°C based on DAQ data analyzed separately were 2.119 J/kg.°C, 2.082 J/kg.°C, and 2.458 J/kg, respectively. The specific heat values were close to those in the reference, with an accuracy of 94.22%, 97.29%, and 99.80%, respectively.

1. INTRODUCTION

Vegetable oil is widely used for cooking and frying in almost all countries worldwide. The design of the optimum cooking and frying system, as well as a basic understanding of the process, is strongly influenced by the thermophysical properties of the materials involved, including the specific heat of the vegetable oil used. Vegetable oil is generally used at 35°C to 180°C (Fasina & Colley, 2008). For this reason, it is necessary to measure the specific heat of vegetable oil that is accurate and reliable, even at high temperatures.

The mixing method is the most commonly used method for measuring the specific heat of materials. This method is done by pouring water with a higher temperature into the material to be measured. However, this method is unsuitable for oil samples, especially at high temperatures, which are insoluble in water and have a higher boiling point. Another common way is to use a DSC calorimeter. This direct method requires only a milligram sample (Hwang & Hayakawa, 1979). However, it requires careful preparation of materials and trained technicians in the laboratory to use them. Besides, these instruments are costly.

The application of the joule calorimeter method is reported to have succeeded in measuring the specific heat of foodstuffs (Muthamizhi *et al*., 2013). This method utilizes the conversion of electrical energy into thermal energy, which causes an increase in the temperature of the sample. However, joule calorimeter devices generally have a less impermeable insulation system so that heat loss can occur during measurement due to the temperature difference between the calorimeter and its surroundings. Thus, the measurement of this method is usually carried out around the ambient temperature. According to Hobani & Elansari (2008), the specific heat of a material is influenced by its temperature. The higher the temperature, the higher the specific heat. Therefore, the measurement of the specific heat of high-temperature vegetable oil based on the Joule experiment needs to consider the effect of heat loss using Newton's cooling correction. This correction compensates for temperature readings during energy conversion based on cooling data when the calorimeter is no longer supplied with electrical energy. Yuningsih *et al*. (2019) report that Newton's correction can reduce errors in mechanical heat equivalence experiments by 2-10%.

The specific heat measurement accuracy is strongly influenced by the measurement accuracy of temperature, time, and converted power. Using a mercury thermometer, stopwatch, and analog multimeter in the joule calorimeter method is considered prone to significant errors due to the low accuracy of these tools and manual reading errors. The development of low-cost Arduino-based data acquisition devices on calorimeters has been successfully carried out by Sulistya (2017) and Vallejo *et al*. (2020) to improve measurement accuracy and precision. Unfortunately, the device did not yet support easy analysis of Newton's cooling correction due to the absence of an automatic power breaker. Therefore, this study aimed to produce a prototype design of a DAQ device that can support the determination of the specific heat of vegetable oil at high temperatures using the Joule experiment and Newton's correction. The prototype was designed to utilize multi-sensors capable of recording data into digital files and actuators that can disconnect power according to heating temperature settings.

2. MATERIALS AND METHODS

Research on the design of the DAQ device was carried out from March to August 2022 at the Food and Postharvest Engineering Laboratory of Universitas Gadjah Mada. The initial research stage, prototype design and construction, consisted of three activities. The first was the determination of the main components and related accessories based on the ease of obtaining hardware with adequate accuracy and the availability of open-source software. The second was designing and manufacturing DAQ device circuits and component layouts. The third was writing, compiling, and uploading program code to the Arduino board using the Arduino IDE. The final research stage, testing the prototype, consisted of testing the sensor's characteristics and the device's performance in determining the specific heat of hot vegetable oil.

2.1. Prototype Design and Construction

The Arduino Mega board with the ATmega 2560 microcontroller chip was the main signal processor equipped with 54 digital I/O pins, 16 analog input pins, and 256 kB flash memory. This microcontroller was chosen because it can be implemented with more sensors and modules at once, the price is relatively low, and it has a wide-open source community. PZEM 003 was selected as a power sensor that can measure voltage (range: 0.05 - 300 VDC, accuracy: ±0.01 V) and current (range: 0.01 – 10 A, accuracy: ±0.01 A). The RTD PT 100 sensor with three terminals was used to measure temperatures between -50 to 400 °C with an accuracy of ±0.015°C. Meanwhile, the time was measured by Real time clock (RTC) DS3231 with an accuracy of ± 3.5 ppm. Other components and accessories in the design included a 5V low-level trigger relay, 20x4 LCD, push button, MAX-31865 amplifier module, and a TTL to serial RS485 converter module. In general, a list of components and their roles in a DAQ device can be seen in Figure 1.

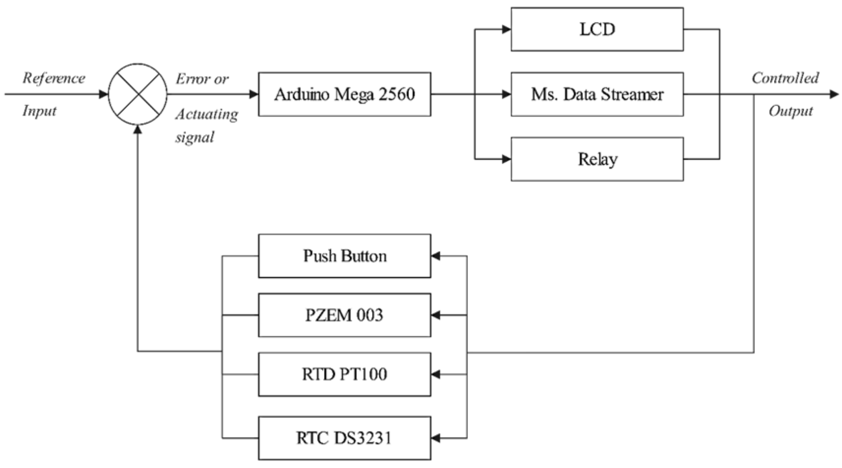


Figure 1. Block diagram for the proposed DAQ device

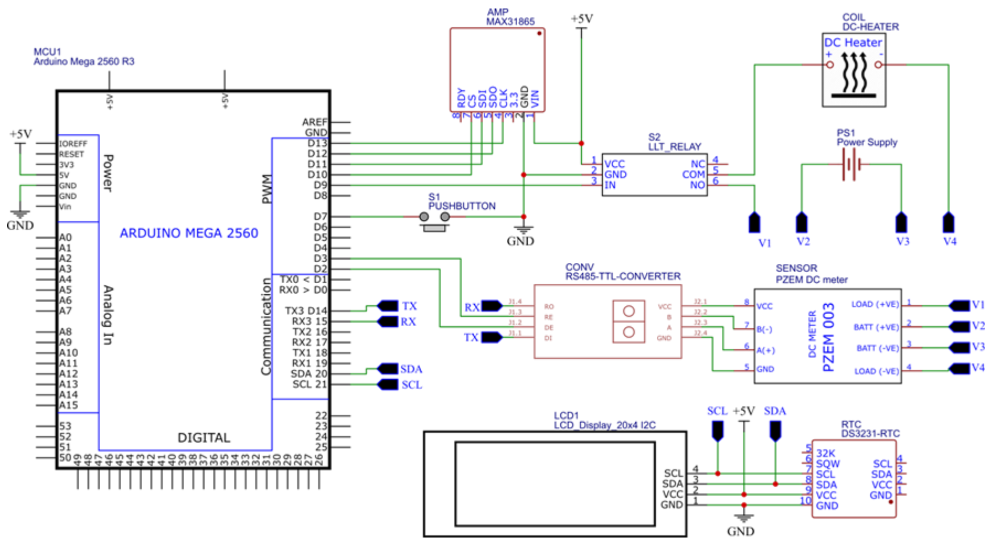


Figure 2. The schematic diagram of the proposed DAQ device

The RTD temperature sensor terminals were connected sequentially to the MAX31865 amplifier module port and then to the Arduino board digital pin. Meanwhile, the PZEM-003 power sensor was connected sequentially to the TTL to the serial-RS485 converter and then to the Arduino board via UART (Universal Asynchronous Receiver/Transmitter) communication. The DS3231 RTC timing module and LCD were connected in parallel to the Arduino board using I2C (Inter-Integrated Circuit) communication. Each hardware component was connected following the wiring diagram in Figure 2. These components were assembled in one acrylic box with dimensions of 26 cm × 11.5 cm × 10 cm.

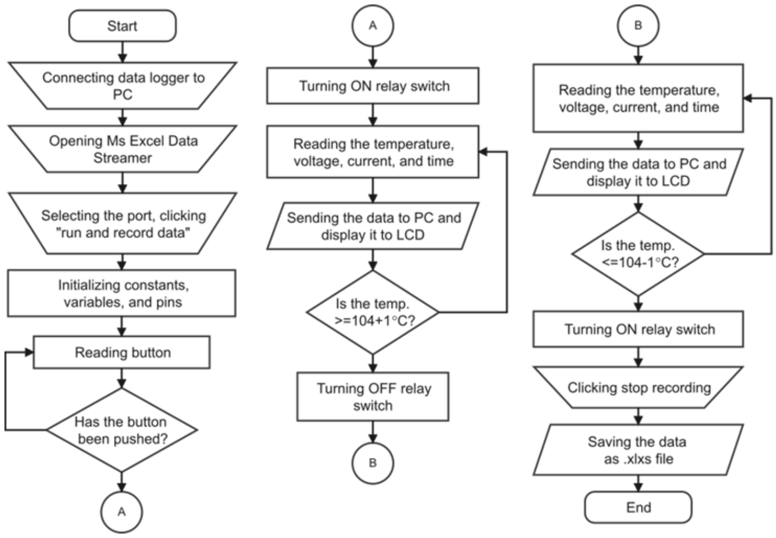
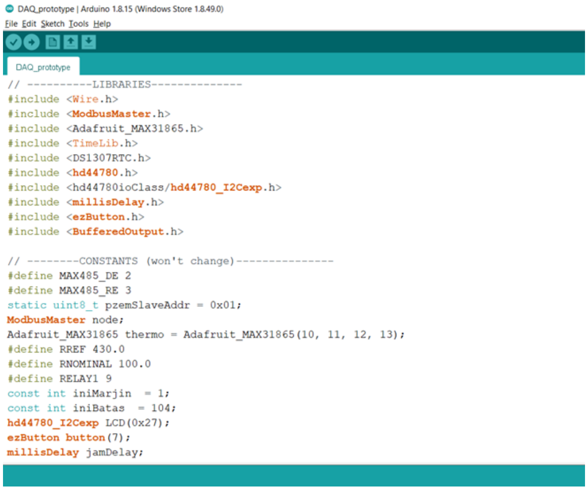


Figure 3. Work process flow chart of the proposed DAQ device

The DAQ software was designed using algorithms following the process flow diagram in Figure 3. When the system was turned on, the ATMega2560 microcontroller would initialize the microcontroller type, data communication speed, and several other variables. When the button was pressed, the counter was checked, followed by readings of temperature, voltage, current, and time to be recorded in the Microsoft Data Streamer and would also be displayed on the LCD. Data recording in real-time from Arduino into an spreadsheet file has been successfully carried out by Putri *et al*. (2015). Unfortunately, the process required the use of additional paid software, LabVIEW. In contrast, Microsoft Data Streamer is a built-in add-in that has been included in the Microsoft Excel package. To ensure that the heating and cooling temperature measurements were met, the heating coil was controlled by a relay with a hysteresis technique. The heating coil was made of constantan wire with a resistance of about 4.3 ohms. According to Bermúdez *et al*. (2020), hysteresis in relays can estimate the energy lost in electrical devices through a delayed operation from a specified threshold value. The threshold in this design was set to 104˚C with a delay of ±1˚C. Thus, the switch would open and cutted off the heating coil current from 105˚C. This position would persist even if the temperature decreased until it reached 103˚C.

Programming code, also known as a sketch, was written in C++ using the Arduino IDE software. Several libraries were used to simplify the creation of the desired program algorithm. The programming code design needed to be compiled first to check for errors. The error-free program was then uploaded to the Arduino board via a USB cable. The initial part of the program code that had been successfully uploaded was shown in Figure 4.




```
// ----------LIBRARIES--------------
#include <Wire.h>
#include <ModbusMaster.h>
#include <Adafruit_MAX31865.h>
#include <TimeLib.h>
#include <DS1307RTC.h>
#include <hd44780.h>
#include <hd44780ioClass/hd44780_I2Cexp.h>
#include <millisDelay.h>
#include <ezButton.h>
#include <BufferedOutput.h>

// --------CONSTANTS (won't change)---------------
#define MAX485_DE 2
#define MAX485_RE 3
static uint8_t pzemSlaveAddr = 0x01;
ModbusMaster node;
Adafruit_MAX31865 thermo = Adafruit_MAX31865(10, 11, 12, 13);
#define RREF 430.0
#define RNOMINAL 100.0
#define RELAY1 9
const int iniMarjin  = 1;
const int iniBatas  = 104;
hd44780_I2Cexp LCD(0x27);
ezButton button(7);
millisDelay jamDelay;
```

Figure 4. Display of the programming code using Arduino IDE

2.2. Prototype Testing

Sensor characterization tests were carried out for accuracy and precision parameters. Sensor accuracy was calculated using Equations (1) and (2), where e is the deviation in percent, N_{com} and N_{DAQ} are the reading values from the commercial measuring instrument and the DAQ prototype, respectively. Meanwhile, the sensor precision was calculated using Equations (3) and (4), where RSD is the relative standard deviation in percent, SD is the standard deviation, and x is the test average (Resmiati & Putra, 2021). A commercial digital multimeter (Kyoritsu 1021R) and thermometer (Mastech MS6514) were used to compare voltage-current and temperature sensors, respectively. Temperature, current, and voltage measurements were carried out in 20.5 - 120.3°C, 0.7 - 2.2 A, and 2.0 - 4.5 V, respectively. Measurements were carried out five times for each observation point.

$$accuracy = 100 - e \tag{1}$$

$$e = \frac{N_{com} - N_{DAQ}}{N_{com}} \times 100 \tag{2}$$

$$precision = 100 - RSD \tag{3}$$

$$RSD = \frac{SD}{\bar{x}} \times 100 \tag{4}$$

Performance testing was carried out by observing the ability of the prototype to support the determination of the specific heat of oil through Joule's law experiments. The DAQ prototype was tested using a Joule calorimeter system consisting of a calorimeter with dimensions of 10.1 cm × 10.1 cm × 17.7 cm, an MDB PS-305DM power supply that can supply a voltage of 0.1 - 30 V and a current of 0.1 - 5 A, and a rheostat of 10 ohms. The DAQ temperature sensor was set so it did not touch the heating coil or interfered with the stirrer.

The converted electrical energy could be calculated from the product of the voltage (V), current (I), and the time the electricity flows (t). According to Joule's law, the amount of electrical energy that flows was equivalent to the thermal energy produced. The thermal energy was used to increase the temperature of the system where the conductor was located, which consisted of a mass of material (m) with a respective specific heat (cp) and a calorimeter with a respective heat capacity (Cd). The heat absorbed by the calorimeter and its supporting devices could not only be calculated from its mass and specific heat because of its complex structure. Therefore, the heat capacity of the calorimeter (Cd) was measured experimentally following the existing method (Sardjito & Yuningsih, 2021; Sulistya, 2017) and obtained a value of 144.98 J/°C for 140 mL distilled water. According to this method, the value of the heat capacity of the calorimeter was affected by the sample volume (surface height) filling the calorimeter vessel. Therefore, the number of vegetable oil samples in this test was made in the same volume, but it was not easy. Thus, the plotting was done based on mass equivalence by measuring the relative density of each vegetable oil using the pycnometer method. Based on the measurements, the pairs of masses and relative density of canola, corn, and sunflower oils at 20°C were 128.03 g (0.9145 g/ml), 128.69 g (0.9192 g/ml), and 129.04 g (0.9217 g/ml), respectively.

The specific heat of vegetable oil was calculated with Newton's correction following the Efeovbokhan and Ohiozua (2013) method. This method applied an electric current from the initial heating temperature (T_1) until it rised 5°C to the final heating temperature (T_2). Data recording continued during cooling until the difference between the highest recorded temperature and the final cooling temperature (q) was 2°C. Newton's cooling correction factor (p) was calculated based on the ratio between the area under the heating curve (A_1) to the area under the cooling curve (A_2) on the graph of the relationship between temperature and time, according to Equation (5). The correction factor would correct the final heating temperature's value so that the sample's specific heat (cp) could be measured using Equation (6). Furthermore, the measurement results were compared with the reference value. In the current prototype, DAQ only functions to acquire data on voltage, current, time, temperature, and to control a relay. Meanwhile, the analysis of specific heat calculations is carried out separately based on the data acquired from the DAQ using Microsoft Excel.

$$p = \frac{A_1}{A_2} q \tag{5}$$

$$c_p = \frac{1}{m}\left(\frac{VIt}{(T_2 + p) - T_1} - Cd\right) \tag{6}$$

3. RESULTS AND DISCUSSION

3.1. Characterization of DAQ Temperature and Power Sensors

Data acquisition is the process of taking real-world signals, including temperature, voltage, and electric current, through sensing and transduction as input to a computer for processing, analysis, and storage. Implementing DAQ in an instrument, including a calorimeter, can support accuracy, precision, and ease of data collection (Albanna et al., 2019). The prototype DAQ device was designed to simultaneously record data from multiple sensors in real time. The physical parameters measured by the sensor were then converted into digital variables with the help of the ADC system embedded in the Arduino microcontroller unit. The prototype of the resulting DAQ device is shown in Figure 5.

The preparation of a sketch program for Arduino utilized several libraries that have the potential to slow down the running of the program, especially in the loop code section. Thus, several evaluations were carried out on time required for Arduino to trace the loop code using the looptimer.check syntax by first installing the loopTimer library. Based on the evaluation results, several program codes were changed to reduce time consumption, such as changing the LCD library from LiquidCrystal.h to hd44780.h and changing the function from delay to millis. The program code improvement saved browsing time from the initial 1,200 ms to only 203 ms. The loopTimer.h library was removed in the last sketch version to lighten the program so that it can support real-time measurements (every second).

Figure 5. The prototype of DAQ device

Table 1. Accuracy and precision of the DAQ device sensor over the measuring range

Parameter	Accuracy (%)	Precision (%)	Range
Voltage	99.97	99.86	2.0 - 4.5 V
Current	99.99	99.86	0.7 - 2.2 A
Temperature	99.97	99.95	20.5 - 120.3°C

Sensor characterization test was carried out, including accuracy and precision, to ensure that the physical parameter values recorded by the DAQ device match the actual values. Accuracy is the level of closeness of the measurement to the actual value or from the measurement results of standardized measuring instruments. Meanwhile, precision is the degree of closeness of the measurement results to the repetition of the exact variable measurement under conditions that do not change or are not much different. Precision is good if the first, second, and so on results are almost the same or close together (Gibson, 2005). The results of the precision and accuracy analysis of the temperature, voltage, and current parameter readings by the DAQ device sensors are shown in Table 1. Based on these data, the accuracy and precision of each sensor used were good, indicated by a value above 95%, which is generally a threshold for instrument quality assessment (Kurniawan, 2019). According to Harmita (2004), the relative standard deviation (coefficient of variation) can be used to determine the level of data precision. If the value is below 2%, then the data is precise.

Furthermore, the ability of DAQ device sensors to measure parameters across various ranges (Table 1) was examined by comparing them to commercial instruments, digital multimeter Kyoritsu 1021R and thermometer Mastech MS6514, that have calibrated sensors (Figure 6). The difference in measured values between the DAQ and commercial instruments for voltage, current, and temperature are 0.052 - 0.117 V, 0.008 - 0.020 A, and 0.350 - 2.301°C, respectively. The increased measured temperature difference may be due to the slower response of the RTD sensor than that of the thermocouple. In general, the data read by the DAQ device sensors are similar to those of commercial instruments, both for voltage, current, and temperature, indicated by a slope value close to 1. However, the calibration equation can be used to modify the output value of the sensor using the inverse principle based on the regression equation (Figure 6). It will process the output value read by the sensor before it is displayed and recorded on the computer, so that the DAQ sensor value can be closer to the value on commercial instruments. For example, to calibrate the temperature output value of the DAQ sensor, this value must first be multiplied by 1/0.9785.

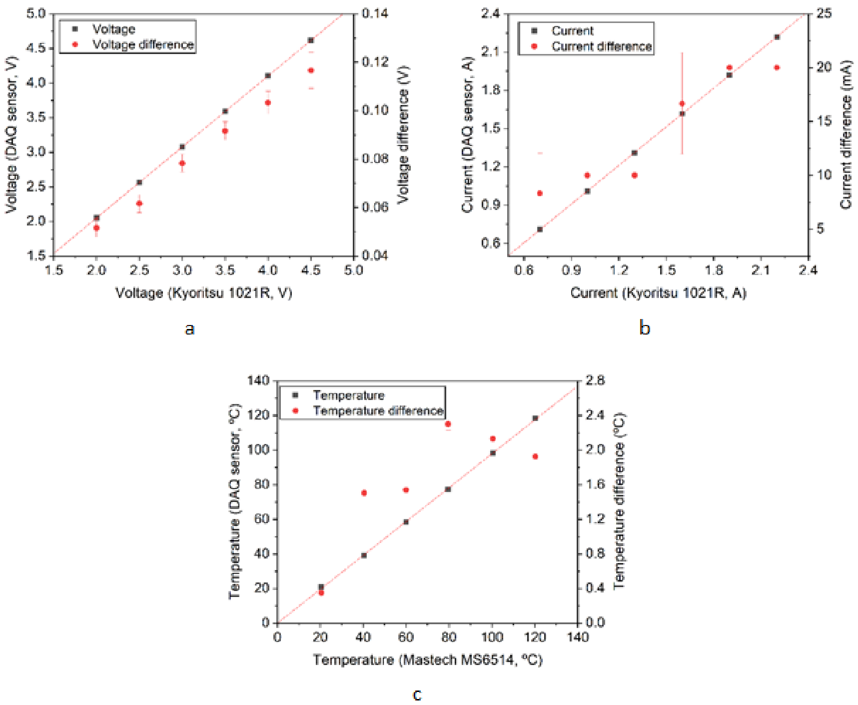


Figure 6. Comparison and difference of measurement results derived from DAQ sensor and commercial instruments for a) voltage with y=1.0259x, b) currents with y=1.0097x, and c) temperature with y=0.9785x

3.2. Performance Test of DAQ Device Prototype in Specific Heat Determination

During the performance test of the DAQ device by Joule's law experiment, the heat supplied to the system through the conversion of electrical energy could raise the temperature of the calorimeter and its contents. Thus, the longer the heating, the higher the system temperature than the ambient temperature. The prototype has only one relay connected to the heating coil to control the heating process based on the temperature setting point (105°C OFF and 103°C ON). The speed of controlling the relay system using the method of Telaumbanua *et al.* (2014) during the heating and cooling stages is about 9.7 minutes and 1.7 minutes, respectively. On the other hand, the response speed of the prototype to the set point to start increasing the temperature takes <1 second (± 230 ms). Even so, the data sampling rate was set to run every second to facilitate manual analysis of the resulting spreadsheet file.

Based on the observations, the temperature of the calorimeter tended to decrease within 2-3 minutes after the power was turned off (Figure 7). This phenomenon indicated that the ability of the Joule calorimeter to insulate heat was poor. This insufficient insulation caused some heat to dissipate to the surroundings during the heating or cooling process, which was indicated by the measured temperature being lower than it should be. Therefore, it was necessary to calculate Newton's correction to determine the actual temperature change.

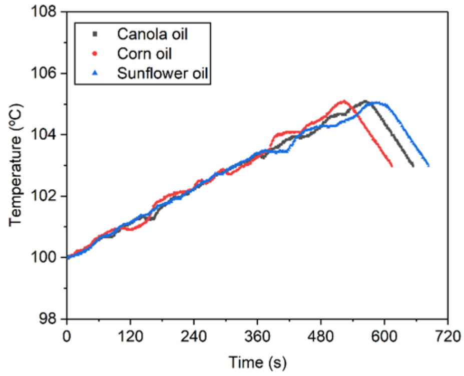


Figure 7. Temperature profile on the heating and cooling process of vegetable oils

The specific heat of vegetable oil at 100°C, either based on calculations from Equation 6 or the reference, is shown in Table 2. The accuracy of specific heat values based on the calculation results of DAQ data against the references (Rojas *et al*., 2013) for canola, corn, and sunflower oils were 94.22%, 97.29%, and 99.80%, respectively. The specific heat of sunflower oil was the highest of all the oils tested, indicating that the energy required to raise its temperature was also the highest compared to the others, even at the same mass and temperature. In other words, sunflower oil took longer to reach a specific cooking temperature when heated at the same heating rate. This proves that the prototype of the DAQ device has been quite successful in supporting the determination of the specific heat of vegetable oil at high temperatures by using Newton's correction. However, the specific heat of canola oil was measured to have a visible difference from that of the reference. This may be due to differences in the fatty acid composition of the samples used, even though the triglycerides were similar in their original state. The specific heat of vegetable oil depends on its fatty acid composition. According to Santos et al. (2005), the specific heat of vegetable oil increases as a function of fatty acid saturation.

Table 2. Specific heat capacities (cp) of the vegetable oils at 100°C

Vegetable oils	Specific heat (J kg^{-1} °C^{-1})	
	DAQ value	Reference value
Canola	2,119	2,249
Corn	2,082	2,140
Sunflower	2,458	2,453

Specific heat can increase with increasing temperature, so it must be considered when calculating heat transfer. According to Fasina & Colley (2008), the increase in specific heat due to temperature in various vegetable oils occurs linearly. The specific heat of vegetable oil at 180°C can be 17% higher than that of 35°C. Higher specific heat means that the energy required to raise the temperature of the oil is also higher per unit mass. In another study by Muthamizhi *et al.* (2013), the phenomenon of an increase in the specific heat of xanthan gum during heating occurs due to the expansion of the material, which makes a small amount of heat flow to the expanding part. Therefore, the existence of a prototype DAQ device is expected to be an affordable solution for measuring and modeling the specific heat of liquid foods at various temperatures using Joule's law experiments and Newton's correction.

However, this prototype still needs to be developed further so that its application is easier and the measurement results are more stable (not fluctuating). Stability can be improved by improving the heat insulation quality of the calorimeter and increasing the responsiveness of the temperature sensor to make it faster. In addition, stirring needs to be automated so that the calorimeter temperature becomes more uniform than in this study.

4. CONCLUSIONS

The prototype DAQ device based on the Arduino Mega board with the ATmega 2560 microcontroller chip has been designed, built, and tested to support the determination of the specific heat of vegetable oil using a Joule calorimeter system with Newton's correction. The developed DAQ device worked with precision and accuracy in continuously monitoring the parameters of voltage, current, and temperature parameters and recording them in a CSV file with a sampling rate of one second. The developed DAQ device offers the advantage of minimizing reading bias so that the resulting data can be used to determine the specific heat of materials even at high temperatures. However, the implementation of this DAQ device needs to be accompanied by improvements to the heat insulation system and automatic stirring on the joule calorimeter to suppress temperature fluctuations.

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