การเปรียบเทียบการตรวจสอบจำนวนฟองก๊าซระหว่างตัวควบคุม Raspberry Pi และ Arduino สำหรับกระบวนการหมัก
Comparison between Raspberry Pi and Arduino controller of gas bubble monitoring for a fermentation process

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บทคัดย่อ
ตัวควบคุมสองประเภทคือ Raspberry Pi3 B และ Arduino mega 2560 ถูกใช้ในเครื่องนับจำนวนฟองก๊าซที่ใช้อุปกรณ์ตรวจจับด้วยแสงเพื่อระบุความก้าวหน้าของการเกิดปฏิกิริยาในกระบวนการหมัก ได้ทำการศึกษาอุณหภูมิที่เหมาะสมและสภาวะการเปิดไฟ-ปิดไฟแสงสว่างที่เหมาะสมของเครื่องนับจำนวนฟองก๊าซ และเปรียบเทียบประสิทธิภาพการนับของชุดตัวควบคุมการนับจำนวนฟองก๊าซที่ควบคุมโดยตัวควบคุมเหล่านี้ในสภาวะที่เหมาะสม พบว่าอุณหภูมิที่เหมาะสมคือ 20-25 องศาเซลเซียส และทำการนับเมื่อเปิดไฟแสงสว่าง นอกจากนี้ยังพบว่าในสภาวะที่เหมาะสมนี้ มีเปอร์เซ็นต์ความผิดพลาดของอุปกรณ์ในการนับจำนวนฟองก๊าซนี้เพิ่มขึ้นตามอัตราการเกิดของจำนวนฟองก๊าซคาร์บอนไดออกไซด์ที่เพิ่มขึ้นในกระบวนการหมัก ซึ่งเปอร์เซ็นต์ความผิดพลาดสูงสุดของคอนโทรลเลอร์ Raspberry Pi3 B คือ 1.5% ในขณะที่ Arduino mega 2560 อยู่ที่ 2.25% ที่อัตราฟองก๊าซ 135 ฟองต่อนาที การเปลี่ยนแปลงของอัตราการเกิดฟองก๊าซคาร์บอนไดออกไซด์มีความสอดคล้องกับการเปลี่ยนที่น่าจะเกิดขึ้นในกระบวนการหมัก ข้อมูลที่ได้จากจำนวนฟองก๊าซที่นับโดยเครื่องนับจำนวนฟองก๊าซนี้สามารถนำไปใช้เพื่อบ่งบอกแนวโน้มของปริมาณเอทิลแอลกอฮอล์ที่ผลิตจากกระบวนการหมักซึ่งสอดคล้องกับความก้าวหน้าของการเกิดปฏิกิริยาในกระบวนการหมักและอัตราการเติบโตของยีสต์

คำสำคัญ: ราสเบอร์รี่พาย อาดุยโน่ ตัวควบคุม การตรวจสอบจำนวนฟองก๊าซ กระบวนการหมัก

Abstract
Two types of controller, Raspberry Pi3 B and Arduino mega 2560, were used in a gas bubble counter equipped with a photo sensor for indicating progress of a fermentation process. The optimum temperature and and switching on/off of the light conditions of the gas bubble counter were studied and the counting performance of the gas bubble counter controlled by these controllers at optimum conditions were compared. It was found that the optimum temperature was 20-25 ^{o}C with turning on the light. It was also found that at optimum conditions, the percentage error of this gas counting device increased with increase of the rate of carbon dioxide gas bubbles produced in the fermentation process. The maximum percentage error of Raspberry Pi3 B controller was 1.5%, while Arduino mega 2560 was 2.25% at bubble rate of 135 bubbles/ minute. In addition, the change of rate of number of carbon dioxide bubbles corresponded to the change that would happen in the fermentation process. Information of the number of gas bubbles counted by the gas bubble counter can also be used to indicate the trend of the amount of ethyl alcohol produced by the fermentation process, which corresponds to the progress of fermentation process and also to the yeast growth rate.

Keywords: Raspberry Pi, Arduino, Controller, Gas Bubble Monitoring, Fermentation Process

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Introduction

It is already known that ethyl alcohol can be produced by a fermentation process using anaerobic microorganisms, where yeast is wildly used. Yeast converts glucose or fructose sugar to alcohol as a main product and carbon dioxide as a by-product. Theoretically, ethyl alcohol will be obtained at about 50% from the amount of sugar used. One molecule of glucose is degraded into 2 molecules of ethyl alcohol and 2 molecules of carbon dioxide gas. The conversion of glucose to alcohol is shown in the following reaction equation (Buchner, 1897) (Enger, *et al.*,1994) (Hopkins,1999).

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \quad (1)$$

Glucose — Ethyl alcohol — Carbon dioxide

Practically, as the fermentation produces many kinds of by-products such as flavoring agents, so a lower value of ethyl alcohol would be obtained. In general, this process produces about 12-15 percent ethyl alcohol for the complete process. In the fermentation process, the number of gas bubbles relates to the number of carbon dioxide molecules and is proportional to the amount of ethyl alcohol. Therefore measuring of the number of carbon dioxide gas bubbles produced in such a reaction can demonstrate the amount of ethyl alcohol product obtained and the trend of the efficiency of the fermentation process (Stanbury, *et al.*, 2016) (Streitwieser, *et al.*, 1981).

In fermentation, the yeast grows rapidly during the first 2-3 days, after that it will slow down until the growth rate is equal to the death rate. However, the amount of ethyl alcohol still increases, while the amount of sugar will reduce, whereas the flavoring agents are created as shown in figure 1. In this period, therefore, the fermentation keeps going even if the yeast has stopped increasing in number. The fermentation temperature affects to the growth rate of yeast, which increases as temperature increases from 10 to 25 ^{o}C, and fermentation time (Surathai, 2010).

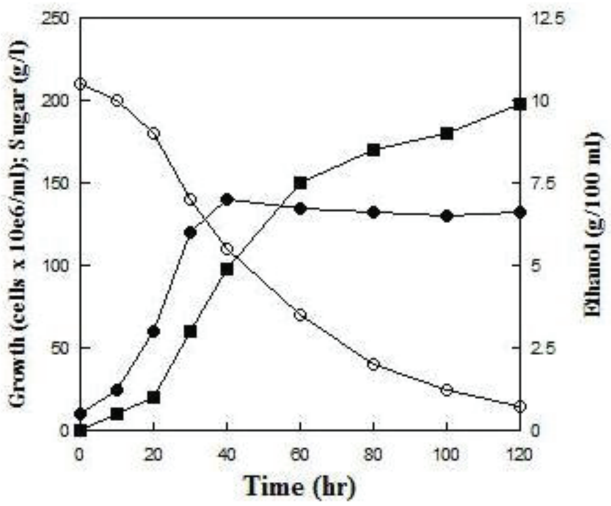


Figure 1 Alcohol fermentation by yeast: yeast (round, solid), alcohol (square solid), and sugar (round, transparent)

The pattern of the growth cycle of microorganisms (Bacterial/Yeast) can be divided into 4 phases: Lag phase; the first phase in which microorganisms begin to find new food and adapt to their environment. Exponential or log phase; a period in which the microbes have increased to the grestest number and have a constant rate of cell division. Stationary phase; a period in which the microorganism has a fixed number, indicating that the microorganism is not increasing in number, and a death phase or decline phase; the last phase in which the microorganisms die (Pornchalermpong, 2019). The pattern of the growth cycle of microorganisms (Bacterial/Yeast) is shown in figure 2.

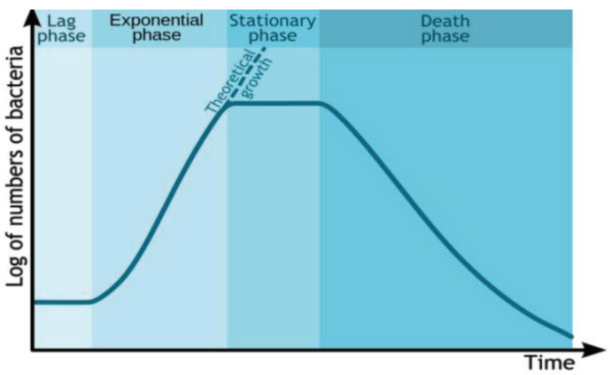
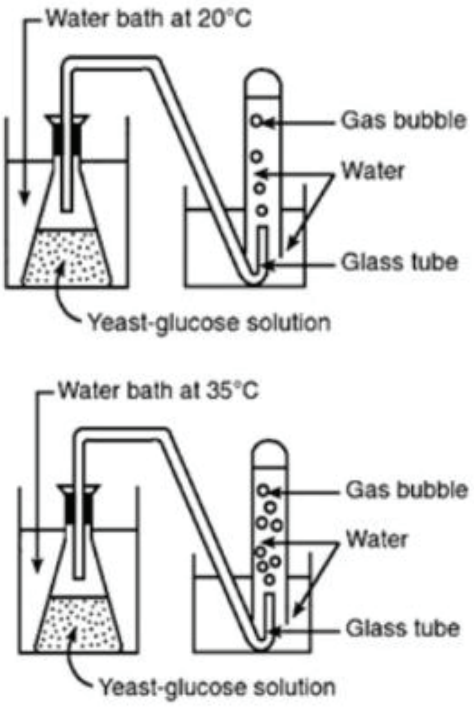


Figure 2 Microorganism: hypothetical Bacterial/Yeast growth curve (Komorniczak, 2012)

The methods of fermentation can be classified in to 2 main types, bottom yeast and top yeast fermentation. The bottom yeast fermentation is a fermentation process taking place at the bottom of the fermentation tank at a temperature of 10-15°C. After fermentation, yeast strains such as *Saccharomyces carlsbergensis* will precipitate at the bottom of the fermentation tank. While, the top yeast fermentation is a fermentation process taking place at the top of the fermentation tank at a temperature of 28-32°C, but can also take place at a temperature of 15-21°C. The yeast species used in this type of fermentation is *Saccharomyces cerevisiae* (Pornchalermpong, 2019). Yeast can grow at 2-40°C, but the production of fermentation will decease if temperature is higher than 35°C (Phoonsiri, 1999).

Malbrough (2019) investigated the effect of temperature on respiration of yeast at 20°C and 35°C by observing the number of CO_2 gas bubble released from the tube as shown in figure 3. It was reported that total number of CO_2 bubble released from the tube at 35°C was higher than at 20°C.



Data Table

Time (minutes)	Total Number of Bubbles Released	
	20°C	35°C
5	0	5
10	5	15
15	15	30
20	30	50
25	45	75

Figure 3 Experimental set up and result of Malbrough's experiment (Malbrough, 2019).

Mulier *et al.* (2009) used a diode laser emitting at 2.68 m to measure CO_2 concentration above a glass poured with a sparking liquid using spectrometer to measure CO_2 concentrations above it such as above beer or champagne as shown in figure 4. The results were presented and compared to a model describing the flux of CO_2 discharging from glasses due to the contribution of bubbles.

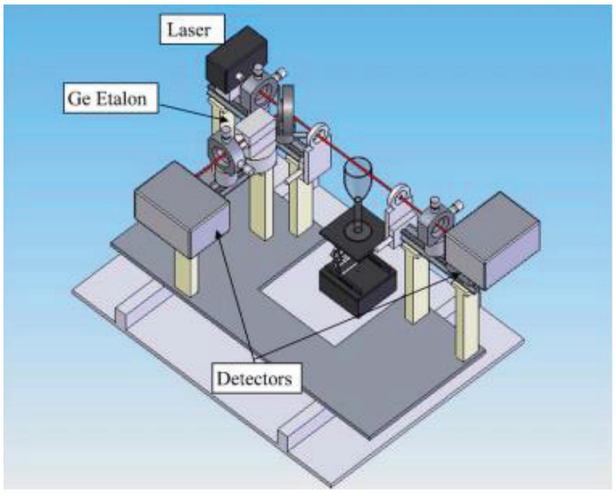


Figure 4 Experimental set up of CO_2 concentrations by infrared laser spectrometer. (Mulier *et al.*, 2009)

Bowler *et al.* (2021) use an ultrasonic sensor to predict alcohol concentration during beer fermentation by using a low-cost ultrasonic sensor combined with machine learning to predict the alcohol concentration during beer fermentation as shown in figure 5. This research demonstrated the potential for a non-invasive sensor to monitor beer fermentation by using inline sensors. This would remove the need for time-consuming manual operation and provide real-time evaluation of the fermenting media.

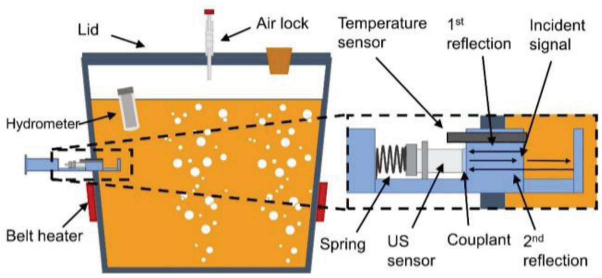


Figure 5 Experimental apparatus and measured US wave reflections (Bowler, *et al.,* 2021)

Conventionally, beer fermentation is typically monitored by periodic sampling and off-line analysis. Since CO_2 produced from fermentation relates to the amount of alcohol produced and also relates to the fermentation process as shown in equation (1) ; if the amount of CO_2 produced can be determined as a real-time measurement, so the amount of alcohol produced could be traced and progress of the fermentation reaction could be monitored. The author has proposed a gas bubble counter to monitor CO_2 produced by using a photo sensor technique integrated with a controller (Wannaprapa, 2018 ; Wannaprapa, 2020). A further study on comparison of two controllers was conducted in this work.

Design and Experiment

The experimental setup for a gas bubble counter consisted of 4 important functional parts: 1) fermenter or experiment glass with shielding to protect from outside light 2) S-shaped glass tube with 2 spherical bulbs 3) photo sensor (photo transmitter (T) and photo receiver (R)), and 4) the processing cycle counts gas bubbles as shown in figure 6.

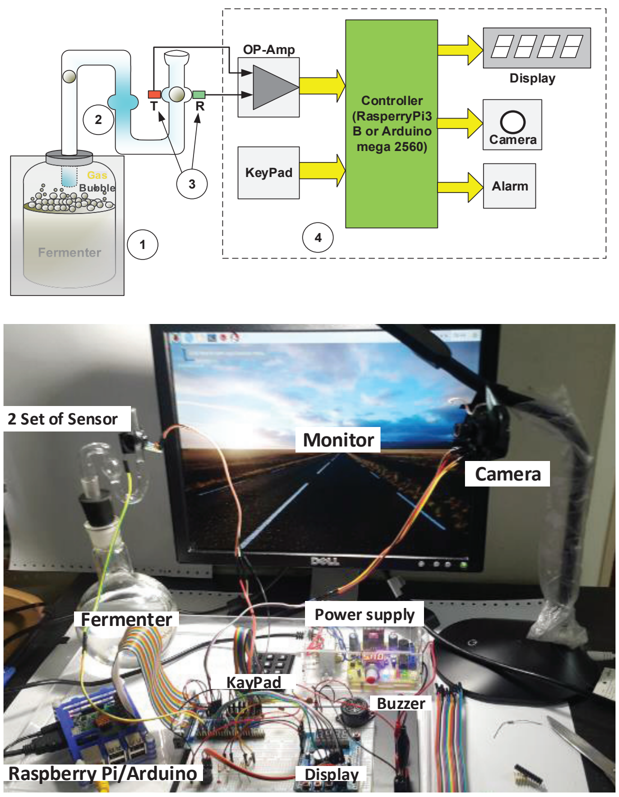
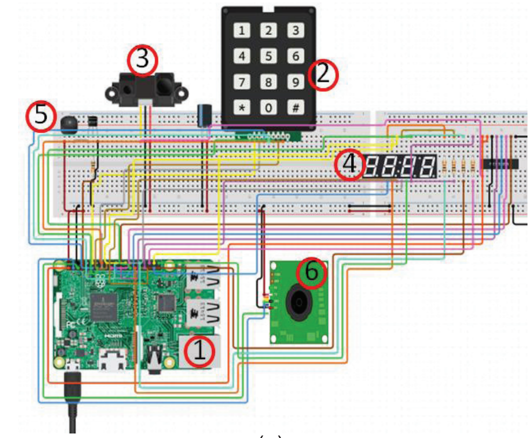


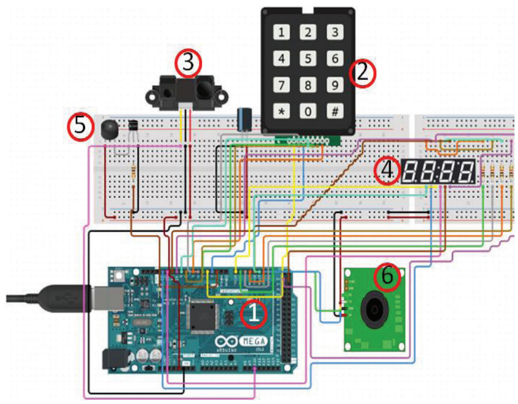
Figure 6 The structure of the gas bubble counter for the fermentation process (Wannaprapa, 2020)

The photo sensor consisted of a photo transmitter diode and a photo receiver diode. The photo transmitter transmitted light at 940 nm. infrared wavelength and the photo receiver received the light transmitted from the transmitter. When there was a gas bubble obstructing this light, the receiver could not detect the light. This criterion was used as an indicator for counting the gas bubble.

The controllers used in this research were Raspberry Pi3 B and Arduino mega 2560. Raspberry Pi is a small single-board computer processor with speeds ranging from 700 MHz to 1.4 GHz and for Pi3 model B is called an “Embedded Computer”. The Arduino mega 2560 is a microcontroller having a speed of 16 MHz. The schematic circuit of the Raspberry Pi 3 model B and Arduino mega 2560 are shown in figure 7.



(a)



(b)

Figure 7 (a) Schematic circuit of Raspberry Pi 3 model B, (b) Schematic circuit of Arduino mega 2560: (1) Raspberry Pi 3 Model B / Arduino mega 2560, (2) KeyPad 4x3, (3) Photo sensor: Opto-diode consists of Transmitter: T and Receiver: R, (4) Display: Seven-segment 4 digits, (5) Buzzer and (6) Camera (Roboplan Technologies Ltd., 2016)

The operation of the gas bubble counter runs as the following steps. First, the bubble number value input from KeyPad is received. Then the Raspberry Pi3 B/Arduino mega 2560 computer processor controller will wait for the signal to count the gas bubbles from the photo sensor installed on the S-shaped glass tube. When each gas bubble was detected, the photo sensor generated a signal and then forward it to the Raspberry Pi3 B/Arduino mega 2560. This signal was counted and compared to the set count value which shows on the display. The result of counting of the number of gas bubbles was shown on a 4-digit 7-segment display. This process will rerun by returning to check the status and waiting for new input value as shown in figure 7. When finishing the task, the controller turned on the buzzer to generate an alarm sound. In addition, this gas bubble counter could also store images during the passage of gas bubbles through the camera, to bring the real time image to compare the bubble count with the gas bubble counter and record number of the gas bubble counted. The operating steps of the bubble counter are shown in figure 8.

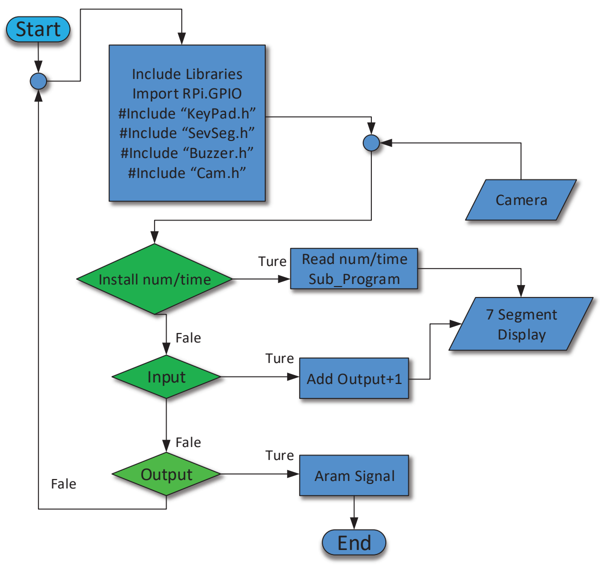


Figure 8 Operating steps of gas bubble counter program (Blum, 2013).

When fermentation takes place, the carbon dioxide will be produced as gas bubbles and then flows in to the S-shape glass tube equipped with the sensor at the spherical glass bulb. The bubble will break up in the first spherical glass bulb resulting in accumulation of ethyl alcohol carried by the bubble's wall as shown in figure 9 (1). As more carbon dioxide is produced and generates high pressure, this gas can push through the ethyl alcohol accumulated at the bottom of S-shape tube and reforms as a gas bubble in the second spherical glass bulb where the sensor is installed as shown in figure 9 (2). This reforming gas bubble is nearly the same size as the second spherical glass bulb and will attenuate the light received by a light's receiver (R) ; this status is called “OFF” as shown in figure 9 (3). A signal will be generated at this criterion and this signal is called “the carbon dioxide bubble count” as shown in figure 9 (3). When there is no gas bubble present inside the spherical glass bulb, the light of the photo sensor's transmitter (T) is able to pass through the spherical glass to the sensor's receiver (R) as shown in figure 9 (4). This status is called “ON” which means the gas bubble does not occur as shown in figures 7 (1), 9 (2) and 9 (4). The bubble formation and bubble detection are shown in figure 9.

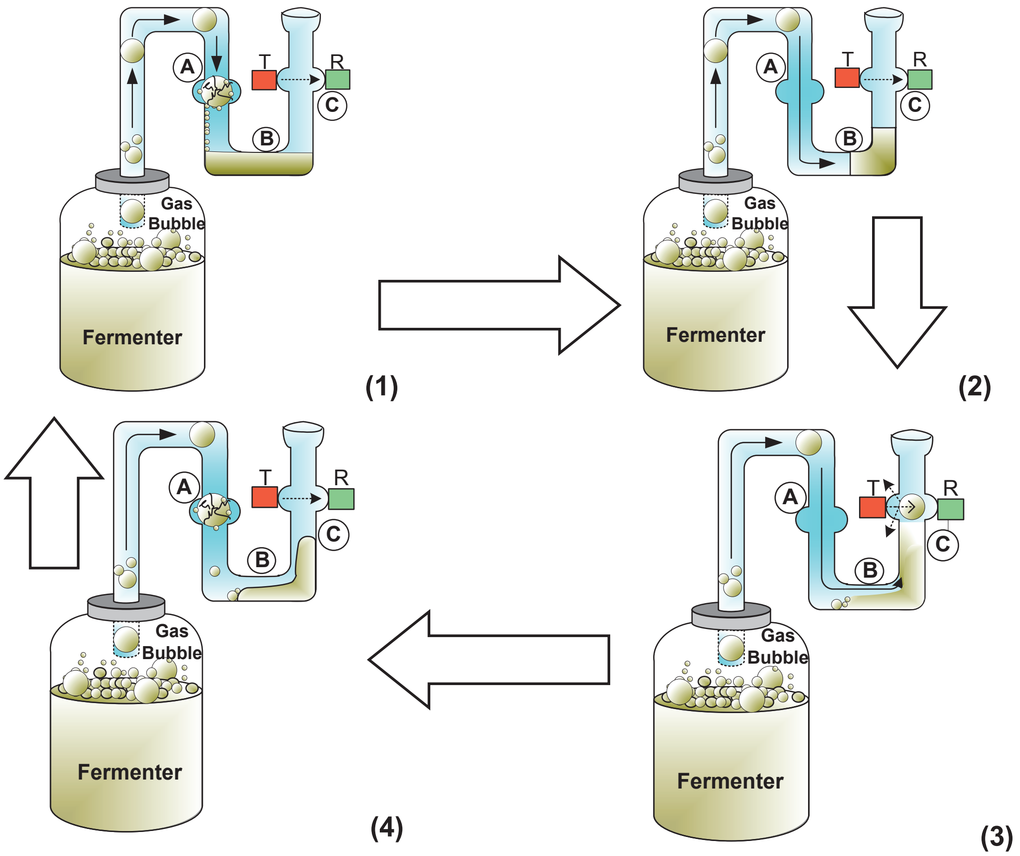


Figure 9 The process of gas bubbles forming inside the S-shaped glass tube and the gas bubble detection: (A) first spherical glass bulb, (B) accumulation of gas and liquid at the bottom, (C) sensor of transmitter T and receiver R installed at second spherical glass bulb (Wannaprapa, 2018)

Top fermentation was used in this research. Two sets of transmitter and sensor were installed at the second spherical glass bulb. One set was connected to Arduino mega 2560 and the other was connected to Raspberry Pi3 B as shown in figure 10.

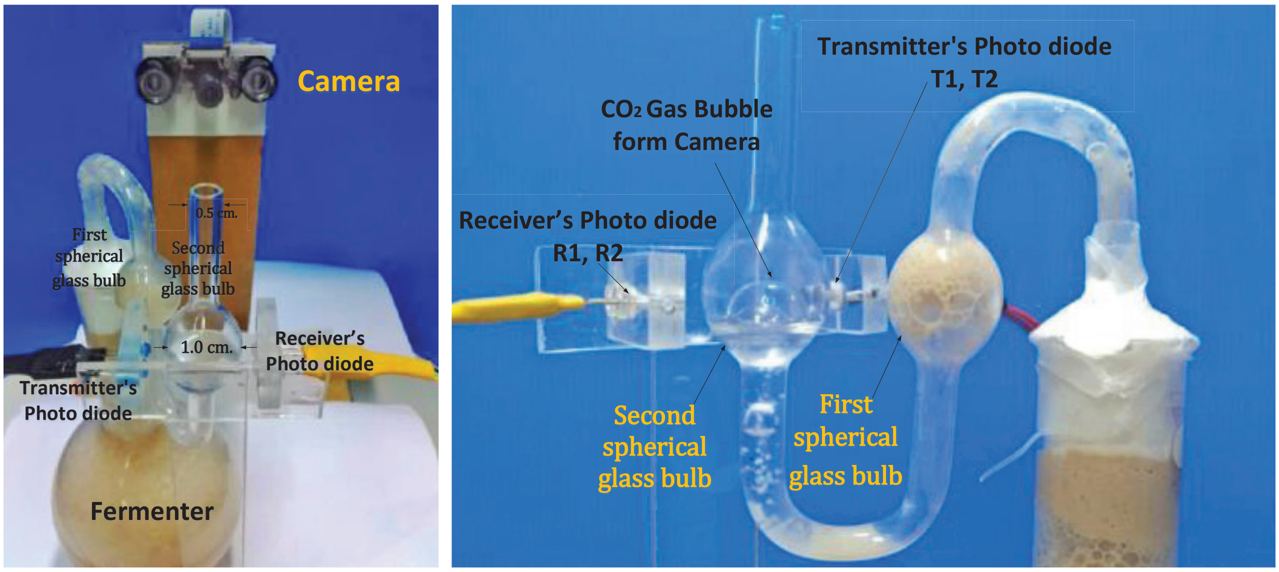


Figure 10 Installation of 2 sets of photo sensor (Opto-diode: T1, T2, R1 and R2 respectively) and CO_2 bubble foaming at spherical glass bulb

A camera equipped with a video recorder was installed at the second spherical glass bulb to record bubble images for further counting by humans. The human counting was conducted by counting the number of gas bubbles obtained from a prerecorded video at 1/10 time of normal speed to achieve accuracy on counting the bubble. The average rates of bubble gas counted by gas bubble counter controlled by Raspberry Pi3 B and controlled by Arduino mega 2560 (Lovine, 2000) were compared to the human counting. The average rate of bubble was calculated from counting the number of gas bubble in every 1 minute for 20 times. This experiment was conducted at temperature range of 15-35°C as the temperature optimum for yeast growth is in the range of 15-21°C (Pornchalermpong, 2019). The experimental period was 15 days for yeasts that grow substantially in the first 2-3 days of fermentation and good fermentation should have a large number of yeast (Surathai, 2010). The investigation of the effect of conditions of ambient light on detection accuracy of gas bubble counting were conducted by turning the light on and off. An experiment to determine accuracy on counting the rate of carbon dioxide bubble of the gas bubble counter compared to human counting was also carried out.

Results and Discussions

The results of the average rate of carbon dioxide bubble counted by the gas bubble counter controlled by the Raspberry Pi3 B, Arduino mega 2560 and by human counting at controller ambient temperature range of 15-35°C at Exponential or log phase are shown in figure 11.

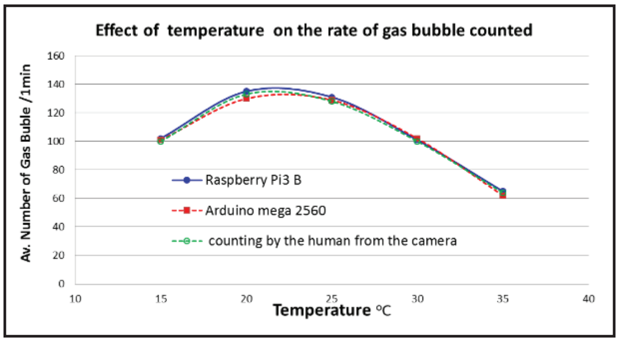
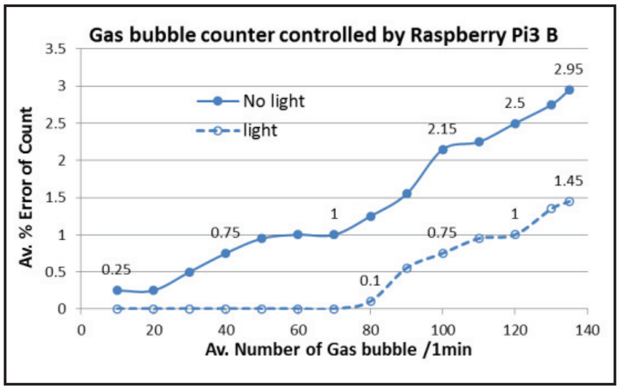


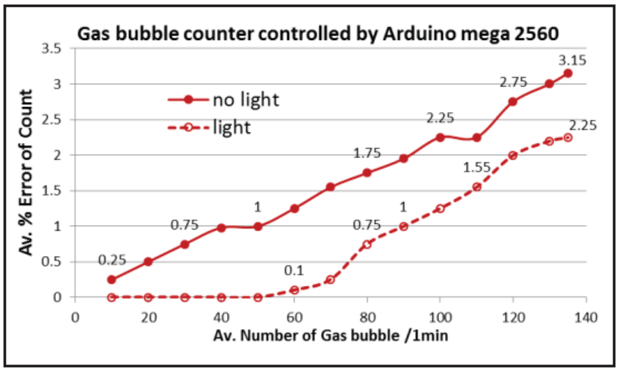
Figure 11 The rate of carbon dioxide bubbles counted at ambient temperature of controller at temperature range of 15-35°C at Exponential or log phase

From figure 11, the average rate of carbon dioxide bubble counted from gas counter controlled by the Raspberry Pi3 B, mega Arduino 2560, and human counting at exponential or log phase increased with increasing temperature and then decreased with further increqse of temperature. The maximum average rate of carbon dioxide bubble counted was shown at temperature of 20-25°C for those three methods. However, temperature range in this experiment (15-35°C) also affected to the growth rate of yeast. Since the growth rate of yeast increases with increase of temperature from 10 to 25°C (Surathai, 2010), while it decreases as temperature higher than 35 °C (Phoonsiri, 1999). Therefore, in this case, the tendency of the rate of gas bubble formation was not due to the counting performance of those two controllers alone, but also corresponded to growth rate of the yeast. It can be concluded that at the ambient temperature of 20-25°C is the optimum temperature for these two controllers was when the highest rate of gas bubbles was obtained.

The percentage errors of results of counting the average rate of gas bubble of gas bubble counter controlled by Arduino mega 2560 and controlled by Raspberry Pi3 B at bubble rate of 0-140 bubbles/minute with the ambient light turning on and turning off are shown in figure 12 (a) and 12 (b) respectively (Pumphrey & Julien, 1996).



(a)



(b)

Figure 12 Percentage errors on counting the average rate of gas bubble of gas counter controlled by (a) Raspberry Pi3 B and (b) Arduino mega 2560 at light turning on and turning off

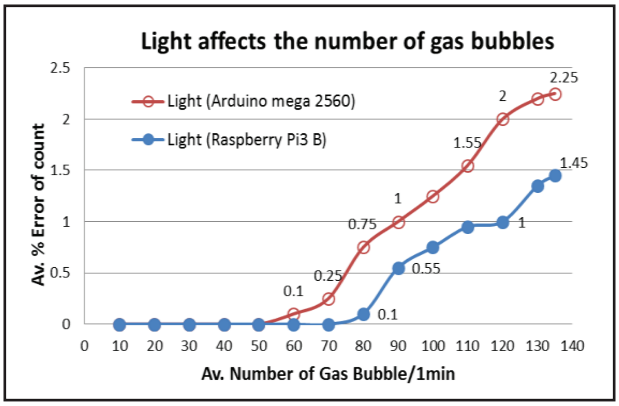


Figure 13 Percentage errors on counting of the gas bubbles controlled by Arduino mega 2560 and controlled by Raspberry Pi3 B with ambient light turning on (Pumphrey & Julien, 1996)

$$\text{Percentage error} = \left| \frac{X_m - X_t}{Xt} \right| \text{X } 100 \qquad (2)$$

Where X_m the number is counted by the sensor and X_t is actual count by human respectively.

Referce to figure 12 (a) and 12 (b) indicates that with ambient light turning on, the percentage error on counting of gas bubble counter controlled by both Arduino mega 2560 and Raspberry Pi3 B did not present problems at low bubble rate and then gradually increase as increase of bubble rate, while with ambient light turning off the percentage error of those two controllers showed at even low bubble rate and gradually increase as increase of bubble rate. This could be caused by when the light was turned on, it enhanced contrast of the gas bubble resulting in higher efficiency of the receiver corresponding to Compomax's article (Compomax, 2022). It can be concluded that the optimum ambient light for these two controllers is with the light turning on.

The comparison of the percentage error on counting the average rate of gas bubble of the gas bubble counter controlled by Arduino mega 2560 and controlled by Raspberry Pi3 B at bubble rate of 0-140 bubbles/minute with the ambient light turning on is shown in figure 13.

Referring to figure 13, at low bubble rate of 10-50 bubbles/minute; there was no percentage error on counting bubble of the gas bubble counter controlled by both Raspberry Pi3 B and Arduino mega 2560. The percentage error of bubble counted by the gas bubble counter is controlled by Arduino mega 2560 gradually increased with increased bubble rate starting from a bubble rate of 50 bubbles/ minute to the maximum value of 2.25% at bubble rate of 135 bubbles/minute. While, the percentage error of bubbles counted is controlled by Raspberry Pi3 B gradually increased as increase of bubble rate starting from bubble rate of 80 to the maximum value of 1.45% at bubble rate of 135 bubbles/ minute. These indicated that Raspberry Pi3 B controller provided lower percentage error than the Arduino mega 2560 controller. In other words, Raspberry Pi3 B controller provided higher accuracy than Arduino mega 2560 controller.

The results of the average rate of carbon dioxide bubbles generated from the fermentation process counted by the gas bubble counter controlled by the Raspberry Pi3 B, Arduino mega 2560 and by humans counting from the image obtained by camera conducted during the fermentation period of 1-15 days are shown in figure 14.

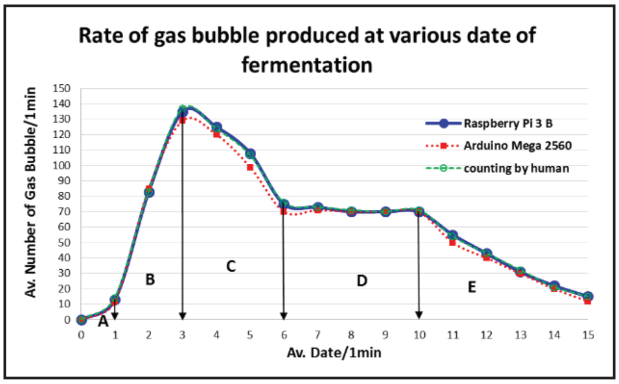


Figure 14 The average rate of carbon dioxide bubble generated from the fermentation process during the average period of 1-15 days/1minute at 25°C counted by the gas bubble counter controlled by Raspberry Pi3 B, Arduino mega 2560, and by human counting (Komorniczak, 2012)

Refering to figure 14, it was found that during 0-1 days of fermentation (A), the average rate of gas bubble generated was 0 to 10 bubbles/minute. This is the beginning of the fermentation reaction corresponding to the first phase or “lag phase” in which microorganisms begin to find new food and environment. During 1-3 days of fermentation (B), the average rate of gas bubble generated significantly increased up to 130-135 bubbles/minute.This indicated that the reaction took place rapidly and was generating a number of gas bubbles, which corresponded to the “exponential phase” or “log phase”. During 3-6 days of fermentation (C), the average rate of bubbles generated gradually decreased from 135 to 70 bubbles/minute. This would be the transition from exponential or log phase to stationary phase. The reason that there are still more gas bubbles produced than there should be as in stationary phase (70 bubbles/minute) might be due to the accumulation of a lot of gas in the fermenter that could not be released; as a result, pressure was developed inside the system. The other explanation would be the exit of the gas was too small and unable to allow gas flow through it (tube size diameter was 0.5 cm). After that, during 6-10 days of fermentation (D), the average rate of gas bubbles generated remained steady at 70 bubbles/minute, which corresponded to “stationary phase” of fermentation. Finally, during 10-15 days of fermentation (E), the average rate of gas bubbles generated drastically decreased to 10 bubbles/ minute, which corresponded to “death phase or decline phase”.

A comparison of the percentage error on the average rate of gas bubbles counted by the gas bubble counter controlled by Raspberry Pi3 B and controlled by Arduino mega 2560 is shown in figure 15.

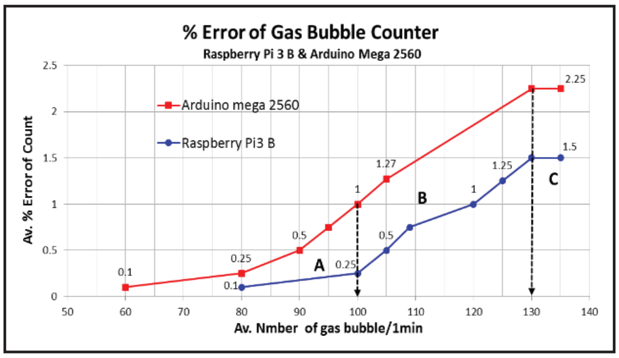


Figure 15 Comparison of percentage error of the gas bubble counter from fermentation process in the range of 60-135 bubbles/minute of the gas bubble counter controlled by Raspberry Pi3 B and controlled by Arduino mega 2560

From figure 15, it is seen that the percentage error on counting of the average rate of gas bubble by the gas bubble counter controlled by two types of controller; Raspberry Pi3 B and Arduino mega 2560, can be divided in to 3 regions. In region “A”, where the fermentation was starting with the average gas bubble rate of 60-100 bubbles/minute, the percentage error of gas bubble counter controlled by Arduino mega 2560 showed a bubble rate of 60 bubbles/minute at 0.1% and increased as bubble rate increaseed up to 1% at bubble rate of 100 bubbles/minute. However, the error of gas the bubble counter controlled by Raspberry Pi3 B showed a bubble rate of 80 bubbles/minute at 0.1% and increased with increased bubble rate up to 0.25% at bubble rate of 100 bubbles/minute. In this region, the percentage error of the Arduino mega 2560 was higher than Raspberry Pi3 B throughout of the region. In region “B”, where the fermentation was proceeding, the average gas bubble rate was 100-130 bubbles/minute, the percentage error of gas bubble counter controlled by Arduino mega 2560 was 1% at bubble rate of 100 bubbles/minute and increased with increase of the bubble rate up to 2.25% at bubble rate of 130 bubbles/minute. However, the percentage error of the gas bubble counter controlled by Raspberry Pi3 B was 0.25% and increased as bubble rate increased up to 1.5% at a bubble rate of 100 bubbles/minute and 130 bubbles/

minute, respectively. In this region, the percentage error of the Arduino mega 2560 was higher than the Raspberry Pi3 B throughout of the region. In region “C”, where the fermentation was at the highest rate with the average gas bubble rate range of 130-135 bubbles/minute, the percentage error of gas bubble counter controlled by both Arduino mega 2560 and Raspberry Pi3 B remained constant at 2.25% and 1.5%, respectively. This indicated that Raspberry Pi3 B controller provided less percentage error than did the Arduino mega 2560 controller. Theoretically, the accuracy of these two controllers should be not much different. However, the error on counting of these controllers would be due to the performance of the photo sensors (transmitters and receivers) used in this work as, even though they are the same model, they were produced in different lots. This leads to the conclusion that the Raspberry Pi3 B controller is more suitable to be used in gas bubble counter than Arduino mega 2560 controller.

Conclusion

The optimum condition for both gas bubble counter controlled by Raspberry Pi3 B controller and by Arduino mega 2560 controller is at temperature of 20-25°C with ambient light turning on. The Raspberry Pi3 B controller provides lower average percentage error than Arduino mega 2560 controller at the working conditions stated above. In conclusion, the gas bubble counter controlled by Raspberry Pi3 B controller is suitable for use in counting carbon dioxide gas produced in order to monitor progress of fermentation. Moreover, the method of counting the average rate of CO_2 gas bubble generated can be used to trace increases of alcohol produced and the growth rate of yeast in the fermentation process. In the future, the gas bubble counter can be applied to detect gas generated by other reactions in close system to monitor the reaction progress such as chemical reactions that produces gas.

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References

Blum, J. (2013). *Exploring arduino: tools and techniques for engineering wizardry*. John Wiley & Sons, Inc.

Bowler, A., Escrig J., Pound M. & Watson, N. (2021). Predicting alcohol concentration during beer fermentation using ultrasonic measurements and machine learning. *Fermentation, 7*, 34.

Buchner, E. (1897). *For his biochemical researches and his discovery of cell-free fermentation*. Munich Germany.

Compomax. (2022). *Basics of Photoelectric Sensing.* http://www.compomax.co.th/product/basics-of-photoelectric-sensing/

Enger, E.D., Kormelink, J.R., Ross, F.C. & Smith, R.J. (1994). *Concepts in biology* (7^{th} ed). Wm. C. Brown Publishers.

Hopkins, W.G. (1999). *Introduction to plant physiology*. John Wiley & Sons. Inc.

Komorniczak, M. (2012). *Microorganism: hypothetical Bacterial/Yeast growth curve*. https://commons.wikimedia.org/wiki/User:M.Komorniczak#/media/File:Bacterial_growt h_en.svg.

Lovine, J. (2000). *PIC microcontroller project book*. McGraw-Hill.

Malbrough, M. (2019). *Energy Relationships: Biochemical pathway.* https://slideplayer.com/slide/3922619/.

Mulier, M., Zeninari, V., Joly, L., Decarpenterie, T., Parvitte, B., Jeandet, P. & Liger-Belair, G. (2009). Development of a compact CO_2 sensor based on near infrared laser technology for enological applications. *Appl Phys B, 94*, 725-733.

Phoonsiri, A. (1999). *Fuzzy Logic Control of Fed-Batch of Saccharomyces cerevisiae TISTR B5020, Unpublished master's thesis*. Prince of Songkla University.

Pornchalermpong, P. (2019). *Generation time*. http://www.foodnetworksolution.com/wiki/word/1543/generation-time.

Pumphrey, B. & Julien, C. (1996). *An introduction to fermentation*. New Brunswick Scientific. (UK) Ltd.

Roboplan Technologies Ltd. (2016). *Schematic circuit of Raspberry Pi*. https://www.circuito.io/app?components

Stanbury, P.F., Whitaker, A. & Hall, S.J. (2016). *Principles of Fermentation Technology* (3rd Edition). Butterworth-Heinemann.

Streitwieser, A., Clayton, Jr. & Heathcock, H. (1981). *Introduction to organic chemistry* (2nd Edition). Macmillan Publishing Co., Inc.

Surathai. (2010). *Yeast & wine fermentation.* https://surathai.wordpress.com/2010/06/12/yeastwine/.

Wannaprapa, M. (2020). A Newly Developed Gas Bubble Counter using Raspberry Pi Controller for Fermentation Process. *Journal of Science and Technology Mahasarakham University. MSU, 3*(3), 251-257

Wannaprapa, M. (2018). Gas Bubble Counters in the Fermentation Process by using Arduino Controller. *Veridian E-journal Science and Technology Silpakorn University*, *6*, 62-73.