Energy Efficiency Improvement in Micro-sized Food Processing Enterprises via Automatic Cooking Gas Control

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Abstract

Food processing is a big industry in many countries. The industry consumes large amount of energy, primarily from liquefied petroleum gas (LPG). Food frying is conventionally controlled via the cooking oil temperature, which is regulated by controlling the amount of heat provided by the cooking gas burner, hence, consumption rate of LPG. For micro-sized food processing enterprises in Thailand, this is usually done manually by operators, resulting in poor energy efficiency and non-negligible amount of waste. To prevent such situations, it is necessary to control the food cooking process more precisely. The objective of this work was to develop a precise control system for a gas cooking stove used to fry rice crackers with an improved energy efficiency and fuel economy. This work reports on the development and testing of an automatic burner control system for an LPG cooking stove used to provide heat in frying Thai rice crackers. The system was based on low-cost sensing of the frying oil temperature and two-step control of gas valves. It was found that the automatic control system employed worked well and more precise control of the frying oil temperature could be achieved. Results of the experimental testing with and without automatic control of the LPG cooking stove in the laboratory setup indicated that better food processing control could give rise to almost 40% improvement in fuel economy for processing rice crackers.

Keywords: energy saving; process control; semi-automation; food engineering; LPG
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1. Introduction

Thailand has long been aiming to become the kitchen of the world. With fertile natural resources, it is a top 10 world leader in production of staple agricultural products including rice, cassava, sugarcane, palm oil, coconut, pineapple and natural rubber [1]. The country is among the world leaders in agricultural product suppliers, due mainly to its well-established food industry. The food industry is the country's 3rd largest industry, contributing nearly a quarter of the country's gross domestic product [2]. There are about 9,000 registered food processing firms in Thailand. Processed food exports contributed more than 50% of total food exports and accounted for about 15% of Thai manufacturing output [3]. Rising costs and energy consumption are crucial issues for the food processing sector [4, 5]. With continuous assistance from governmental offices, Thai manufacturing

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companies have been investing substantial capital in research and development to increase their operational performances. Many firms are utilizing smart information and communications technology to control their manufacturing processes. This is particularly true for medium and large companies. However, for small and micro-sized enterprises, adopting advanced technologies remains a tremendous challenge. Development of food processing machinery and energy efficient equipment appropriate for these small and micro-sized enterprises is therefore of great importance [6].

Most people prefer cooking with gas [7] such as liquefied petroleum gas (LPG), since it is a clean-burning and efficient cooking fuel. It has been a fuel choice for many urban and rural households [8]. Consumption of cooking gas or LPG in Thailand is about seven million tons a year, in which the households sector (including small business operators) accounts for about a third (32%) or more than two million tons a year [9]. Thailand has been in the process of adjusting the retail LPG price structure to reflect actual capital costs, which hurts the household sector, as well as small and micro-sized food processing enterprises. Most related research on improvement in cooking stove efficiency is concerned with equipment redesign and modification [10-16]. To the authors' knowledge, there are no reports in existing literature on developing and applying automatic control to household gas cooking stoves.

Control of cooking is traditionally done manually and is rather inaccurate. This is especially true for small and micro-sized enterprises using deep fat frying for preparation of popular snacks such as rice crackers. The process is about the interaction between oil and food at high temperatures, which dehydrates and cooks the food, resulting in physical and chemical changes. A typical operation and end products are shown in Figure 1. This usually leads to the possibility of the product being over- or under-cooked, hence, defected products and high energy cost. Precise process control is therefore desirable to improve product quality, energy saving and reduce defects.

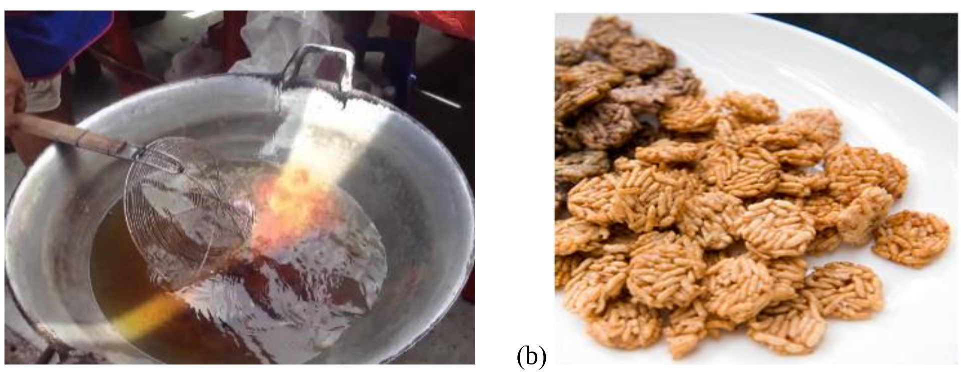
(a)  (b)

Figure 1. (a) food frying operation; (b) produced rice crackers.

The objective of this work was to develop a cost effective, automatic burner control system for a gas cooking stove used to fry rice crackers. It was aimed at increasing the energy efficiency and reducing food waste by using a low-cost sensor for the frying oil temperature and two-step control of the gas valves. Control algorithms for LPG supply and cooking process stability were specifically designed for this application.

2. Materials and Methods

2.1 Frying process control

In the fast frying process of making rice crackers, cooking oil must be kept at high temperature, preferably around 200ºC. Dry precooked rice is cooked very quickly (about 20-30 s) by immersion in hot oil. Frying is a method that entails simultaneous heat and mass transfer, wherein frying oil acts as the heat transfer medium, while moisture moves outwards and the oil is engrossed into the food [17]. The process control model was developed (Figure 2), as follows;

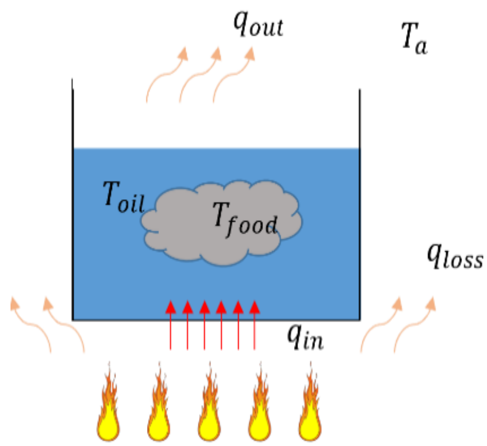


Figure 2. Physical model of food frying process.

From an energy balance*:*

$$q_{in} = q_{acc} + q_{out} + q_{loss} \quad (1)$$

where q_{in} *and* q_{loss} are heat input and heat loss. Accumulated heat (q_{acc}) and heat out to atmosphere (q_{out}) are:

$$q_{acc} = \frac{d}{dt}\left(m_{oil}C_{p,o}\left(T_{oil} - T_{oil,0}\right) + m_{food}C_{p,f}\left(T_{food} - T_{food,0}\right)\right)$$

$$q_{out} = hA(T_{oil} - T_a)$$

where m_{oil}, m_{food}, $C_{p,o}$, $C_{p,f}$, T_{oil}, T_{food}, $T_{oil,0}$, $T_{food,0}$ and T_a are masses, specific heat capacities, and instantaneous and initial temperatures of oil and food, and surrounding air temperature respectively. *A* and *h* are oil surface area and convective heat transfer coefficient. Then

$$\frac{d}{dt}\left(m_{oil}C_{p,o}T_{oil} + m_{food}C_{p,f}T_{food}\right) + hA(T_{oil} - T_a) + q_{loss} = q_{in}$$

Or

$$m_{oil}C_{p,o}\,\dot{T}_{oil} + m_{food}C_{p,f}\dot{T}_{food} + hAT_{oil} - hAT_a + q_{loss} = q_{in}$$

Let

$$Q_{predict} = m_{food}C_{p,f}\dot{T}_{food} - hAT_a + q_{loss}$$

Hence

$$m_{oil}C_{p,o}\,\dot{T}_{oil} + hAT_{oil} + Q_{predict} = q_{in}$$

Finally, the control equation for the heat input is:

$$q_{in} = Q_{predict} + u$$

where

$$m_{oil}C_{p,o}\,\dot{T}_{oil} + hAT_{oil} = u \tag{2}$$

This is a first order equation describing the oil temperature, with the heat loss (q_{loss}) as a disturbance. The relationship between the input (u) and output (T_{oil}) may be written as the following transfer function,

$$G(s) = \frac{T_{oil}(s)}{U(s)} = \frac{1}{m_{oil}C_{p,o}s+hA}$$

The transfer function, $G(s)$, represents a first-order dynamic system with time-constant (τ)

$$\tau = \frac{m_{oil}C_{p,o}}{hA}$$

For optimal control problems, on-off control law [18] ideally produces a solution in the shortest time. In practice, the on-off control system may be suitable for the first order system such as that seen in heat transfer.

2.2 Control system setup

Simple and cost effective control systems may be used to create step control action. In this simple setup, there are three levels of gas flow: no flow (off), medium flow and, high-flow which are implemented by a two-valve system. The automatic oil temperature control system was designed and built. This economical control system tailored made for gas cooking consists of a thermometer, a flame detector, a spark ignitor, two-stage main gas valve and regulator, connected to an electronic control board. The system is compact and can be easily installed on an existing gas cooking stove, shown in Figure 3.

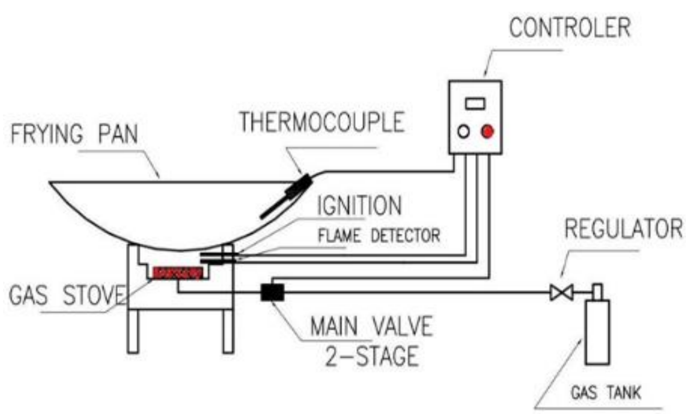


Figure 3. Schematic of the control system setup

The control system setup was based on industrial modular process controllers (Delta DVP16B for main PLC control, Siemens LMB 21.330C2 for burner control, and Fuji PXF4 for temperature control). A human operator can set up the program and monitor the process using a human machine interface (HMI). Control box diagram and hardware setup are shown in Figures 4 and 5.

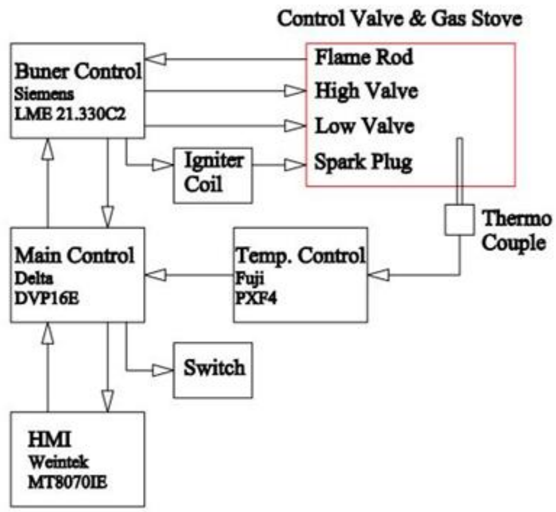


Figure 4. Control box diagram

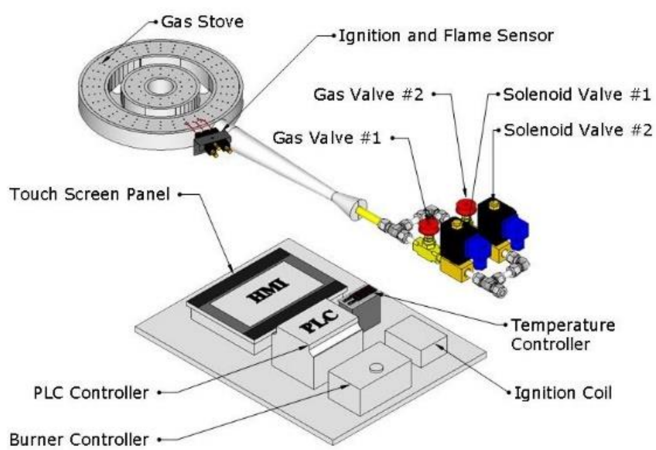


Figure 5. Hardware design for the control system setup

2.3 Test setup, procedure and evaluation

The control system was installed and experimentally tested on a gas cooking stove used in rice cracker frying. It was connected to an LPG cylinder and data logger. Figure 6 shows a laboratory setup for testing the control system with a frying set. The LPG mass was measured via a load cell with a full scale of 30-kg and 5-g resolution. The oil temperature was measured using a type-K thermocouple. For each run, about 10 liters of frying oil was initially used. The oil was started cold. For tests without the control system, the operator would adjust the main valve and ignite manually. Once the operator felt that the oil was sufficiently hot with oil temperature around 180-210^{o}C, he/she would then start loading about 1 kg of dry precooked rice or raw rice crackers into the frying pan. When the rice crackers turned golden yellow and floated at the top of the oil layer, indicating that they were well cooked, they were then removed to a plate. For tests with the control system, the oil temperature was preset at 200°C. At the start, the control system would ignite and adjust the gas valves automatically. Once the preset temperature was reached, the operator would be notified, he/she would then start processing the snacks in a similar manner to the former case. The quantity of rice crackers, frying oil, and LPG before and after processing were monitored. About 300 kg of raw rice crackers were processed in about 20 test runs. Comparison between the manual and automatic systems was based on the following performance indicators; noise-to-signal ratio for oil temperature evolution, LPG consumption rate, specific energy consumption and potential reduction in greenhouse gas emission.

Figure 6. Setup for testing the control system with a gas cooking stove and a frying pan

The noise-to-signal ratio is the indicator used to identify a control factor and measure how the response varies relative to the target value. Here, it was used to evaluate the size of the temperature difference from the target (noise) or temperature fluctuation against the target temperature (signal).

$$N/S = \frac{\Delta T}{T} \tag{3}$$

Specific energy consumption (in MJ/$kg_{product}$) was the measure of energy requirement to process a unit of product. Here, it was determined from the cooking gas energy used per unit mass of processed rice crackers. The heating value of LPG used was 50 MJ/kg.

$$\text{SEC} = \frac{m_f HV_f}{m_p} \tag{4}$$

The reduction in greenhouse gas emissions (in kg-CO_2/$kg_{product}$) was a measure of the environmental benefit of the process by its reduced equivalent carbon emission. Here, it was determined from the amount of prevented CO_2 emission per unit mass of processed rice crackers.

$$R_{CO2} = \frac{m_{CO2}}{m_p} \tag{5}$$

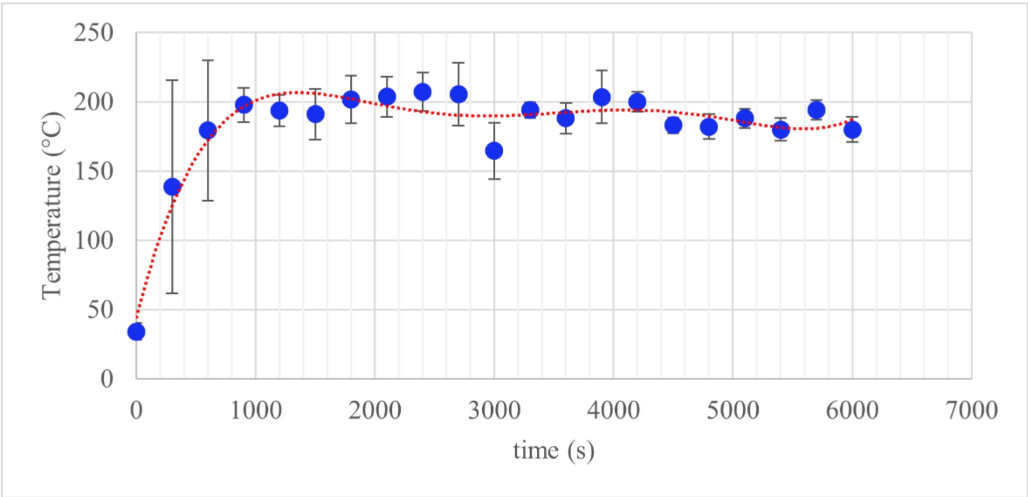
3. Results and Discussion

For a typical frying operation of rice crackers, loading of the dry precooked rice and removing of the cooked rice crackers from the oil pan are carried out intermittently. The frying oil temperature drops when the dry precooked rice is loaded into the pan. The operator will normally increase the LPG feed to raise the oil temperature. If a large load of rice is put in at one time, a large drop in temperature is witnessed.

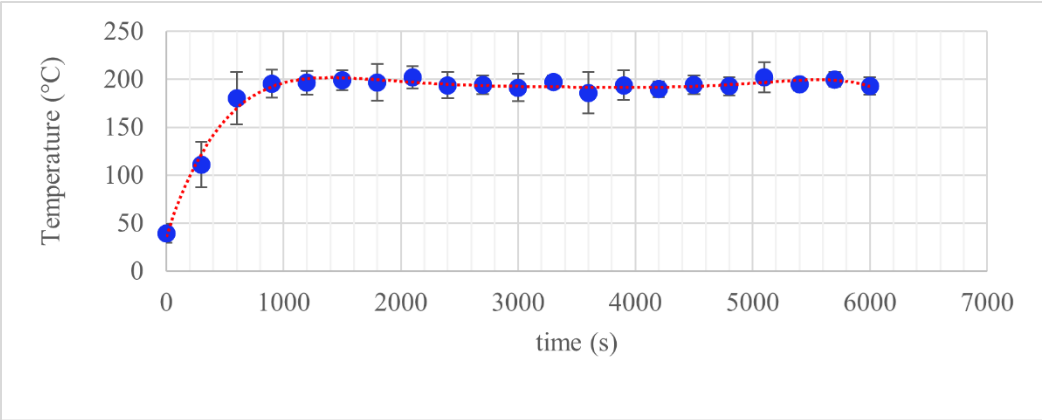
From these experiments, Figure 7 displays the variation of oil temperature with time during typical frying operation with and without the control system, respectively. Average temperature evolution is illustrated with error bars showing the standard deviation of data and dotted lines showing the trends. Both cases were carried out by the same experienced operator. For the former case, the frying oil temperature was intermittently adjusted manually via a main LPG valve by the operator, while for the latter case, the operator concentrated solely on the food products by allowing oil temperature regulation by the control system. During the initial heating up from room (30ºC) to target temperature (200ºC), both cases showed a similar heating rate and time of about 15 min, prior to the start of food frying. Short stabilization time was also allowed once the set temperature was reached before the start of each frying. As anticipated, it was found that larger error bar ranges were evident for experimental frying without automatic control. It was clear that with the automatic control system on, the frying oil temperature was able to stabilize mostly near the preset value of 200ºC with an average N/S ratio of around 5%. Larger variation in temperature was apparent for the manual control with maximum N/S ratio as large as 20%. The trend line (shown as dotted lines) for the case with automatic control was able to more closely follow the set temperature than the one with manual control.

Figure 8 illustrates LPG consumption rate during the frying with and without the control system. A number of test runs were carried out. Examples of several runs were shown here for operation with and without automatic control as square and round symbols, respectively. Their averages were displayed as solid lines. From the findings, it was found that operation with the control system consumed the fuel gas at a lower rate than that without the control system, from 0.185 g/s to about 0.120 g/s, a reduction of more than 35%. Taking into account the gas consumption used for heating up and processing from the start-to-finish, the overall fuel consumptions per unit mass of processed rice crackers were found to be 0.060 and 0.096 kg/kg for frying with and without the automatic control. The resulting SECs were 3.0 MJ/kg for operation with the automatic control, compared to 4.8 MJ/kg for operation with the manual control. This was a 37.5% saving in energy consumption. To justify its cost effectiveness, a simple period to positive cash flow or payback period analysis was estimated, taking into account the initial investment cost against the LPG cost saving. The term “simple” was used because no discount rate was considered here. The proposed control system required an investment of about 35,000 THB. For a small processed food vendor consuming 1200 kg of LPG a year, saving in fuel cost of about 10,800 THB could be obtained (with LPG price of 24 THB/kg). This gave rise to a simple payback period of about 3.2 years. With higher amount of LPG consumed or with governmental subsidy, the return on investment would be shorter.

With regards to potential CO_2 reduction, about 0.036 kg LPG was saved in processing 1 kg of rice crackers. According to the United Nations Intergovernmental Panel on Climate Change guidelines, released CO_2 from LPG usage is given as 3.12 kg CO_2/kg. Therefore, the reduced greenhouse gas emission was 0.112 kg CO_2/ kg product. With around 1,000 tons of yearly production of processed rice crackers, the anticipated reduction potential of CO_2 was approximated to be in excess of 110 tons per year in total.



(a)



(b)

Figure 7. Change in frying oil temperature during typical food processing operation (a) without and (b) with control

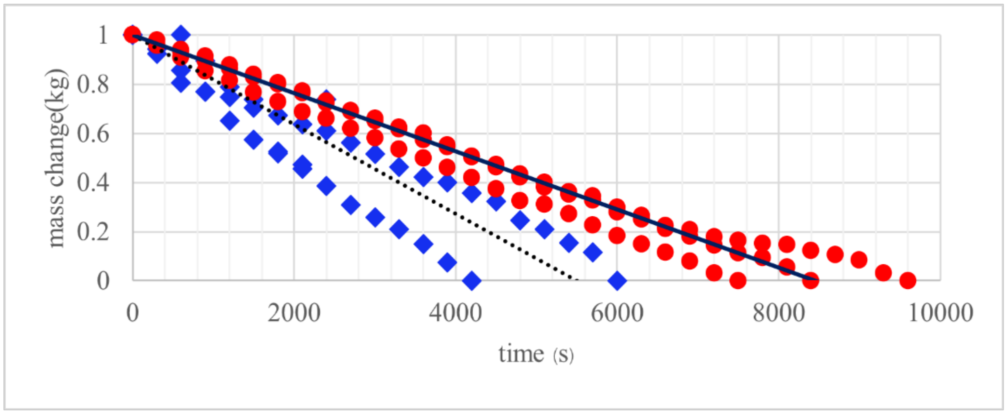


Figure 8. LPG consumption rate during a typical rice cracker frying operation with (diamond symbol) and without (round symbol) the control system

As far as the quality of food products was concerned, it was inspected and evaluated visually and sensually by experienced workers and entrepreneurs who have been in this business for many years. As anticipated, the product appearances, texture and taste were found to be similar and comparable between those obtained from both sets of tests, according to shop owners and food processing operators. From their personal assessment, they confirmed that the quality of the food products was satisfactory. However, based on the food processing point of view, any process modifications can affect product quality to varying degrees. Therefore, the assessments of color, texture, and other key quality aspects should be objectively and/or subjectively evaluated .For sensory evaluation, it requires at least 10-trained panelists or 30 non-trained panelists .The results, based from statistical analysis on quality aspects, must be acceptable. This exercise should be conducted in the future study. From general observation, a smoother operation was realized, but reduction in waste generation was rather marginal. Controlled food processing offered more savings in fuel and energy, compared to that without control. Switching from manual to automatic control was confirmed to improve productivity in terms of fuel economy, energy efficiency for this operation.

4. Conclusions

In this work, a cost effective, automatic burner control system was developed and designed specifically for micro- and small enterprises as well as household gas cooking stoves. It was based on regulating and stabilizing the temperature of the frying oil. Tests with rice cracker frying were conducted and the performance was compared between operating with and without the burner control system. Standard low-cost sensors and two-step control of gas valves proved to be acceptable, achieving smoother operation and a reduced LPG consumption during the trial runs. Energy efficiency was increased and food waste due to over- and under-cooked was reduced. Fuel saving, hence savings in the operating cost was successfully demonstrated. Cost analysis results showed that the control system may be feasible. Simple payback period was estimated to be about 3.2 years. Adoption of the gas burner control system appeared to give better process control, simpler operation, enhanced energy saving and potential reduction in CO_2 emissions for micro-sized food processing enterprises.

5. Acknowledgements

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References

[1] Office of Agricultural Economics, 2019. *Agricultural Economic Information*. [online] Available at: www.oae.go.th/view/1/Information.

[2] Federation of Thai Industries, 2020. *Knowledge Management*. [online] Available at: www.fti.or.th.

[3] National Food Institute, 2020. *Food Intelligence Center Thailand*. [online] Available at: www.nfi.or.th.

[4] Ladha-Sabur A., Bakalis, S., Fryer, P.J. and Lopez-Quiroga, E., 2019. Mapping energy consumption in food manufacturing. *Trends in Food Science & Technology*, 86, 270-280.

[5] Jagtap, S., Rahimifard, S. and Duong, L.N.K., 2019. Real-time data collection to improve energy efficiency: a case stury of food manufacturer. *Journal of Food Processing and Preservation*, 2019, https://doi.org/10.1111/jfpp.14338.

[6] Clairand, J., Briceno-Leon, M., Escriva-Escriva, G. and Pantaleo, A.M., 2020. Review of energy efficiency technologies in the food industry: trends, barriers, and opportunities. *IEEE Access*, 8, 48015-48029.

[7] Suwansri, S., Moran, J.C., Aggarangsi, P., Tippayawong, N., Bunkham, A. and Rerkkriangkrai, P., 2014. A biomethane solution to domestic cooking in Thailand. *Energy for Sustainable Development*, 23, 68-77.

[8] Grieshop, A.P., Marshall, J.D. and Kandlika, M., 2011. Health and climate benefits of cookstove replacement options. *Energy Policy*, 12(12), 7530-7542.

[9] Energy Policy and Planning Office -Ministry of Energy, 2020. *Annual Energy Statistics 2018*. [online] Available at: www.eppo.go.th.

[10] Jugjai, S., Tia, S. and Trewetasksorn, W. 2001. Thermal efficiency improvement of an LPG gas cooker by a swirling central flame. *International Journal of Energy Research*, 25, 657-674.

[11] Das, T., Subramanian, R., Chakkaravarthi, A., Singh, V., Ali, S.Z. and Bordoloi, P.K., 2006. Energy conservation in domestoc rice cooking. *Journal of Food Engineering*, 75(2), 156-166.

[12] Suwansri, S., Moran, J.C., Aggarangsi, P., Tippayawong, N., Bunkham, A. and Rerkkriangkrai, P., 2015. Converting LPG stoves to use biomethane. *Distributed Generation and Alternative Energy Journal*, 30(1), 38-57.

[13] Shinede, Y.H., Gudekar, A.S., Chavan, P.V., Pandit, A.B. and Joshi, J.B., 2016. Design and development of energy efficient continuous cooking system. *Journal of Food Engineering*, 168, 231-239.

[14] Ogedengbe, E.O.B. and Ajibade, F.D., 2017. Improved burner efficiency and fuel consumption in domestic cooking appliances. *Energy and Policy Research*, 4(1), 29-35.

[15] Kaushik, L.K., Deb, S. and Muthukumar, P., 2018. Energy saving and techno-economic assessment of self aspirated domestic LPG stove with porous radiant burner. *IOP Conference*

Series: Materials Science and Engineering, 377, 012194, https://doi.org/10.1088/1757-899X/ 377/1/012194.

[16] Mishra, N.K. and Muthukumar, P., 2018. Development and testing of energy efficient and environment friendly porous radiant burner operating on liquefied petroleum gas. *Applied Thermal Engineering*, 129, 482-489.

[17] Oke, E.K., Idowu, M.A., Sobukola, O.P., Adeyeye, S.A.O. and Akinsola, A.O., 2018. Frying of food: a critical review. *Journal of Culinary Science and Technology*, 16(2), 107-127.

[18] Lewis, F.L., Varabie, D.L. and Syrmos, V.L., 2012. *Optimal Control.* 3rd ed. Singapore: Wiley.