# Development of Rotary Drum Dryer for Oil Palm Sterilization

Sherly Hanifarianty

A Thesis Submitted in Fulfillment of the Requirements for the
Degree of Master of Engineering in Energy Technology
Prince of Songkla University
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**Thesis Title** Development of Rotary Drum Dryer for Oil Palm Sterilization

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**Major Program** Energy Technology

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I hereby certify that this work has not been accepted in substance for any degree, and is not being currently submitted in candidature for any degree.

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**Academic Year** 2017

## ABSTRACT

In the small oil palm industry, the sterilization process consumes a lot of energy during heating. The purposes of sterilization process are to soften fruit, inactivate enzymes, reduce water content in fruit and facilitate oil extraction. During the sterilization process in conventional drying, it was found that oil palm did not heated uniformly between the top and the bottom layers of the drying chamber, and the process take about 30 hours. Therefore, the rotary drum dryer is being developed as a new device for drying oil palm, to solve problem of over-drying, to maintain good quality and accelerating the drying process. This research aims to design and develop a rotary drum dryer for oil palm sterilization. The outcome of research is to perform an important model of drying technology that can be adopted in the sterilization process in the oil palm industry for increasing sterilization process efficiency and minimizing energy consumption. The fixed parameter of this research was drying temperature in the drum at 120°C which was the same to conventional dryer whereas the variable parameters were rotation speeds varied in the range of 1.68, 4.14, and 8.34 rev/h and the number of ventilation holes of the drum varied for each side lid in the range of 9, 18 and 36 holes, respectively. Therefore, the moisture ratio (MR) of oil palm, energy consumption and CPO quality (color and FFA) of rotary drum drier compare to batch drier were evaluated in this research. Additionally, the flow behavior and heat transfer of rotary drum dryer were also studied by using Computational Fluid Dynamics (CFD). For the case of CFD, the ventilation holes were studied at various holes for each side lid namely, 6, 8, 12 and 18 holes. At 1,400 and 1,600 seconds for 12 ventilation holes showed the uniform temperature distribution for the whole inside the drum. In this study, variation of rotation speeds and ventilation holes give small effect on moisture ratio in every experimental cases.

For energy consumption, rotation speed of 1.68 rev/h with ventilation hole of 36 and rotation speed of 8.34 rev/h with ventilation hole of 36 showed the lowest fuel consumption of 0.49 $kg_{LPG}$ per hour. For specific energy consumption value, rotation speed of 8.34 rev/h with ventilation hole of 9 shows the highest specific energy consumption (SEC) value of 9.326 $MJ/kg_{dried\ palm}$. Whereas, batch drying presents the lowest specific energy consumption (SEC) value 4.496 $MJ/kg_{dried\ palm}$. Moreover, for specific moisture evaporation rate value, rotation speed of 4.14 rev/h with ventilation hole of 18 represents the highest specific moisture evaporation rate (SMER) value of 2.829 $MJ/kg_{water\ removed}$/hour. And then, batch drying shows the lowest specific moisture evaporation rate (SMER) value of 0.501 $MJ/kg_{water\ removed}$/hour. For dried palm quality, at first for color appearance at rotation speed of 1.68 rev/h with ventilation hole of 36 drying period of 9 hours perform cook dried palm. At the same time, for dried palm quality of batch dryer bottom layer performed cooked palm with colorless of kernel and brownish color of mesocarp. Second, FFA percentage of rotary drum dryer has higher value than that of batch dryer. In factory, the drying process take time about 30 – 40 hours to achieved good condition of dried palm. For future, it needs to consider energy cost compared to factory. This study also suggested that velocity flow and temperature distribution with different ventilation holes and temperature variations have to be studied further.

**Keywords:** Oil palm drying, Rotary dryer, Batch dryer, Ventilation hole, Rotation speed, Computational fluid dynamics

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**Sherly Hanifarianty**

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# LIST OF FIGURES

# LIST OF PAPERS AND PROCEEDINGS

This thesis is based on the following papers, referred to their order of experimental design in the text. The publications are attached as appendices at the end of the thesis.

**Paper 1** S. Hanifarianty, T. Theppaya, C. Nuntadusit, M. Wae-hayee. 2018. The effect of ventilation hole on flow behaviour and heat transfer of rotary drum dryer. **This manuscript has been published in Journal of Advanced Research in Fluid Mechanic and Thermal Science, Volume 46(1) pp. 62 - 72. Indexed by Scopus.**

**Paper 2** S. Hanifarianty, A. Alimalbari, T. Theppaya, M. Wae-hayee. 2018. Effects of temperature variation through drying bed on appearance of dried palm fruit in a lab-scale batch dryer. **This manuscript is being drafted.**

**Paper 3** S. Hanifarianty, A. Alimalbari, T. Theppaya, M. Wae-hayee. 2018. Development of rotary drum dryer for defoliate oil palm sterilization. **This manuscript is being drafted.**

**Proceeding 1** S. Hanifarianty, A. Legwiriyakul, A. Alimalbari, C. Nuntadusit, T. Theppaya. M. Wae-hayee. 2018. A rotary drum dryer for palm sterilization: preliminary study of flow and heat transfer using CFD. The 8th Thai Society of Mechanical Engineers, International Conference on Mechanical Engineering (TSME-ICoME 2017), Bangkok, Thailand, December 12th **-** 15th 2017. **Indexed by Scopus.**

**Proceeding 2** S. Hanifarianty, A. Legwiriyakul, A. Alimalbari, C. Nuntadusit, T. Theppaya. M. Wae-hayee. 2018. The development of rotary drum dryer for palm fruit sterilization. The 8th Thai Society of Mechanical Engineers, International Conference on Mechanical Engineering (TSME-ICoME 2017), Bangkok, Thailand, December 12th **-** 15th 2017. **Indexed by Scopus.**

# CHAPTER 1
# INTRODUCTION

## 1.1 Introduction

The oil palm is commercial planting that have good oil yield when compared with other plantations. There are two type of oil palm milling factories that are small and large factories. For large factory, the process mostly uses steam at 140°C for about 75 – 90 minutes to stop free fatty acid formation and to soften the oil palm (Kamal, 2003). The raw material is the bunch of oil palm. This process produces crude palm oil (CPO) and crude palm kernel oil (CPKO). Crude oil palm is obtained from the mesocarp and is orange in color, while crude palm kernel oil comes from the kernel in the nut and is white in color. Crude oil palm is processed in an oil palm milling machine when the kernels are removed from the nuts, and it is one example of by-product from this process.

In Thailand, the small oil palm industry sterilization process uses a batch chamber for about 30 hours. In the small oil palm industry, sterilization consumes a lot of energy compared to other processes. This process could stop enzyme reaction that oxidizes and disturbs the mesocarp cell, and continues the oil extraction process. Falling or defoliate oil palm fruit from farmers are mostly used as raw material. During batch sterilization, oil palm is heated with hot air by a grill burner. The source of its hot air comes from firewood or fuel oil as shown in Figure 1.1. In this process, the oil palm needs to be turned over periodically; hence workers are needed to flip it during this time.

In the grilling process, several problems have been found in that oil palm was burned due to exposure to direct fire and not heated well. Oil palm at the bottom of the dryer is dried faster than at the top. During the grilling process, workers must turn over the oil palm from the bottom to the top or otherwise turn it over from top to the bottom. In addition, it takes about 30 hours to dry the oil palm fruits.

A rotary drum dryer could be used as an alternative drying process in the small oil palm industry. This kind of alternative drying process is shown in Figure 1.2. It processes through direct heating from fire at the bottom of the drum. In the figure, the lid functions as a door which is opened and closed to put oil palm into the drum. The oil palm is mixed together in rotary drum, which transfers heat from the burner to the rotary drum. To start the heating process, the burner is heated by firewood as fuel oil from below the burner. Then, the drum is rotated to mix heating oil palm.

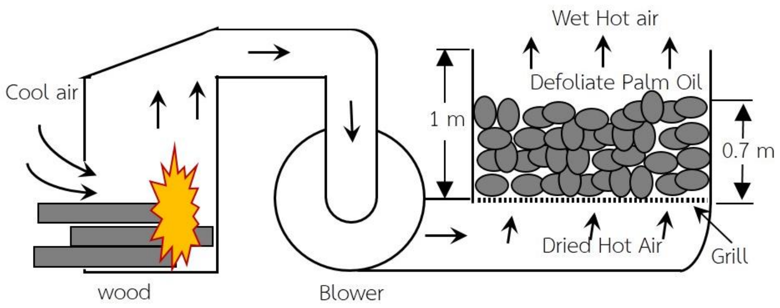



Figure 1.1. Diagram of drying palm fruit in factory

This research aims to design and develop a rotary drum dryer for the oil palm sterilization process. The outcome of research is to perform an important model of heat transfer that can be adopted in the sterilization process in the oil palm industry for increasing sterilization process efficiency and minimizing energy consumption.

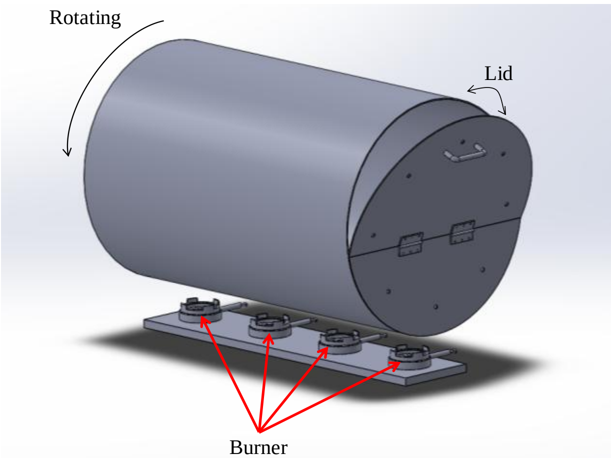



Figure 1.2. Rotary drum dryer

The fixed parameter of this research is temperature, whereas the variable parameters are rotation speed and the number of ventilation holes of the drum. The temperature inside rotating drum is an important factor in avoiding over-heating in drying process to make it in good quality product. The speed of the rotary drum also plays an important role to make heat distribute to oil palm while the amount of ventilation holes will be used to evaporate the moisture of the oil palm fruit.

## 1.2 Literature review

The drying technology most commonly used in industry is the rotary drum drying (Figure 1.3.). It works like cylindrical container that rotates along its longitudinal axis continuously (Alonso et al., 2017). Throughout the process, gases pass though out the counter flow. There are three basic forms of rotary drum, slipping, cascading and cataracting and 7 classifications of subtype motion used (Mellmann, 2001).

The slipping motion includes sliding and surging throughout the process. This is never used in industry application, due to low product quality. The cascading motion consists of slumping, rolling and cascading process. The cascading physical motion is mixing, which is applied in the rotary drum process and can produce a high quality and uniform product because of favorable conditions for heat transfer even in high temperature performance (Mellmann, 2001). The cataracting motion has subtypes of cataracting and centrifuging, for which its physical process are crushing and centrifuging. It is used in ball mills for industrial application. It is also reported that there are some factors that affect the motion inside the rotary drum, such as size, shape, density and angle (Alonso et al., 2017).

Figure 1.3. This shows the mechanical construction of the heat rotary dryer that can reduce moisture content of product by direct or indirect contact of hot gas. The rotary drum dryer can work under high temperature and is able to produce a uniform quality of product (Alonso et al., 2017). During the process, it is rotated and moisture is evaporated along with exhaust gas. It is easy to operate, low maintenance and has wide application in various industries as shown in Figure 1.4.

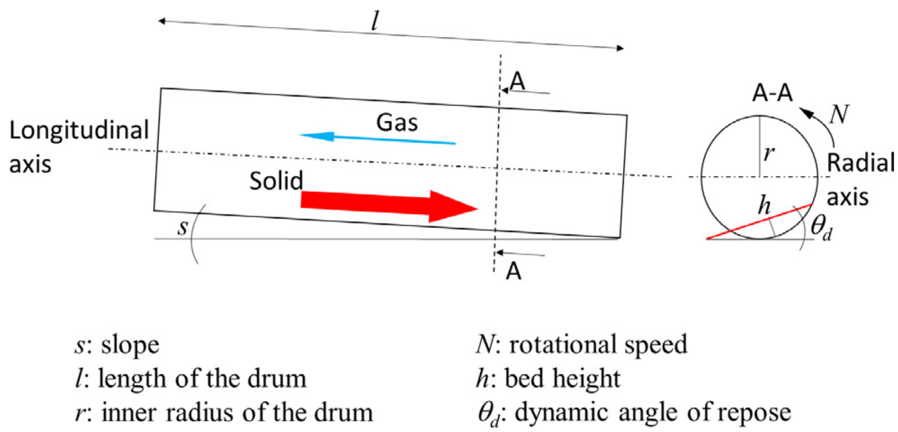



Figure 1.3. Industrial rotary drum (Alonso et al., 2017)

Simpraditpan et al. (2010) studied the effect of temperature of rotary drum dryer and batch dryer of plastic pellets drying (Figure 1.5.). They found that rotary drum dryer at 120°C for 4 hours give better quality than batch drum dryer. The result showed that good moisture content and drying quality of product from rotary drum dryer.

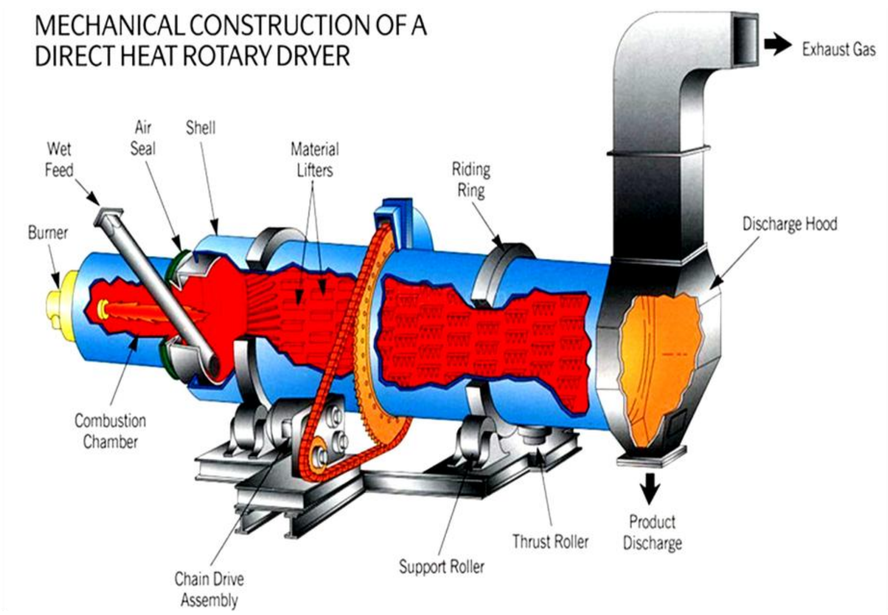



Figure 1.4. Principle structure of rotary drum dryer (http://rotarydryer.org/products)

Firouzi et al. (2017) studied about energy consumption and rice milling quality between conventional industrial batch type bed dryer (Figure 1.6.) and industrial horizontal rotary dryer (Figure 1.7.). They proved that industrial horizontal rotary dryer showed better result in 9% of final moisture content for saving energy in drying process.

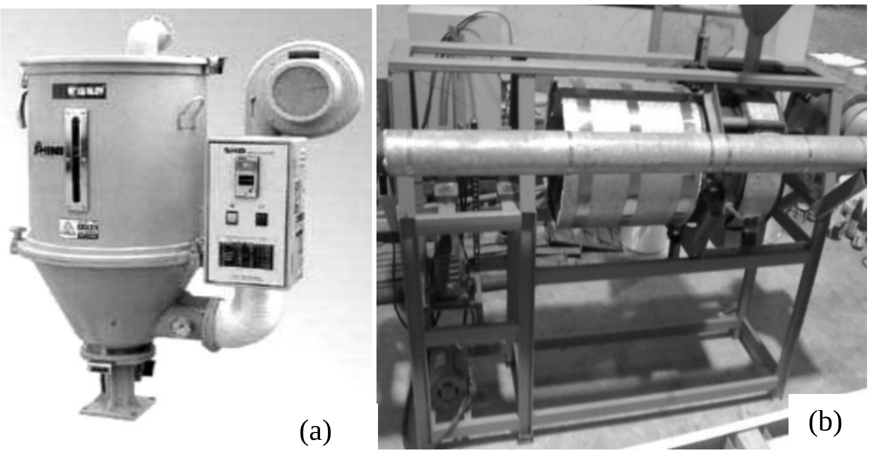



Figure 1.5. (a) Batch drum dryer (b) Rotary drum dryer (Simpraditpan et al., 2010)

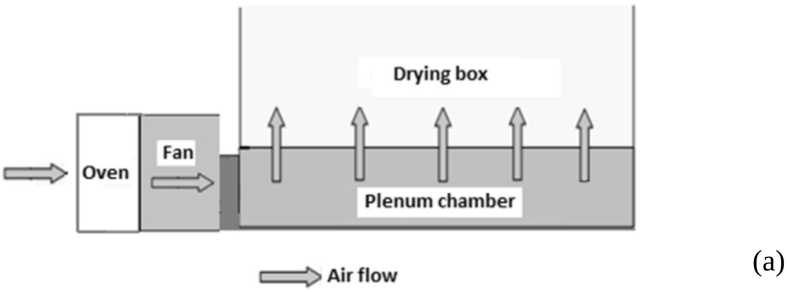



Figure 1.6. Conventional industrial batch-type bed dryer (Firouzi et al., 2017)

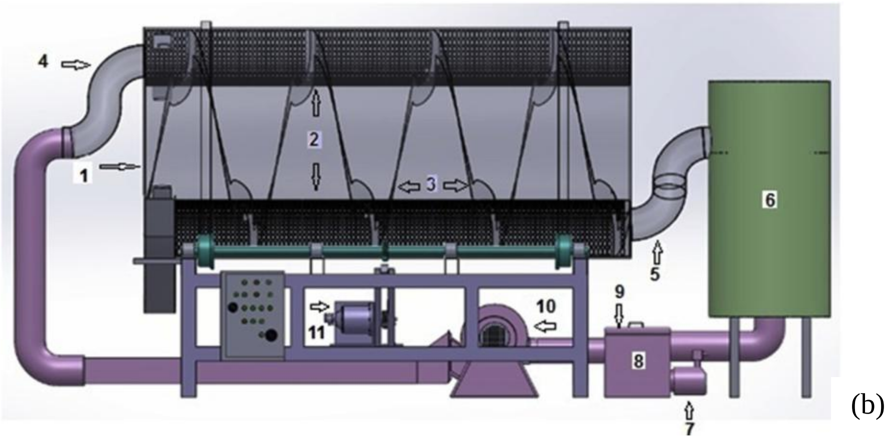



Figure 1.7. Industrial horizontal rotary dryer (Firouzi et al., 2017)

Alonso et al. (2017) reported that rotary drums in solar thermal applications give positive effects such as good mixing and homogeneous distribution of temperature inside the chamber. Performance during the process could be enhanced by using a high speed rotating and stirring element, but this also could depend on the characteristics of the material being dried. Re-radiation and conduction should be a concern, as it is a source heat loss during the process. There are ways to reduce heat loss such as using insulator improvement.

For oil palm sterilization, Umudee et al. (2013) studied about oil palm sterilization using microwave irradiation. It was found that sterilization of oil palm using microwave at 50-80°C is the optimum temperature for heating oil palm. But, for this kind of irradiation heating process is limited to industrial for future used.

Yunus et al. (2016) investigated about oil palm sterilization using high pressure. It proved that at 70 psi (temperature of about 150°C) for 30 minutes showed better in sugar content, release more oil and absorb more water.

For defoliate palm fruit, it processed through conventional batch drying process. In the factory, several problems have been found that oil palm was burned due to exposure to direct fire and not heated well. Oil palm at the bottom of the dryer is dried faster than at the top. During the grilling process, workers must turn over the oil palm from the bottom to the top or otherwise turn it over from top to the bottom. In addition, it takes about 30 hours to dry the oil palm fruits.

A rotary drum dryer could be used as an alternative drying process in the small oil palm industry. It processes through direct heating from fire at the bottom of the drum. The temperature inside rotating drum is an important factor in avoiding over-heating in drying process to make it in good quality product. The speed of the rotary drum also plays an important role to make heat distribute to oil palm while the amount of ventilation holes will be used to evaporate the moisture of the oil palm fruit.

## 1.3 Objectives

Aims of this research are:

1. To study the effect of temperature variation on appearance of dried palm fruit in a lab-scale batch dryer.
2. To develop rotary drum dryer for a new method of drying oil palm.
3. To decrease the period of drying time.
4. To study flow and heat transfer behaviour of hot air in rotary drum dryer.

## 1.4 Scopes of the study

The scopes of the study are:

1. Oil palm drying process weighing of 50 kg.
2. LPG as burner fuel, due to easy to control temperature of a drum dryer.

# CHAPTER 2
# RESEARCH METHODOLOGY

## 2.1 To design a rotary drum

This activity would design and perform a rotary drum with a direct-heating as shown in Figure 2.1. The figure shows a 200-litre volume of rotary drum. The rotary drum has length of 90 cm and diameter of 55 cm. The rotary drum would be contained approximately 50 kg of oil palm, which was 1/3 of total volume of the drum. The rotary drum dryer would have an open side position to set a lid up for entering and removing the palm. Both lid and the end of the drum would be designed with ventilation holes to remove moisture from the drum.

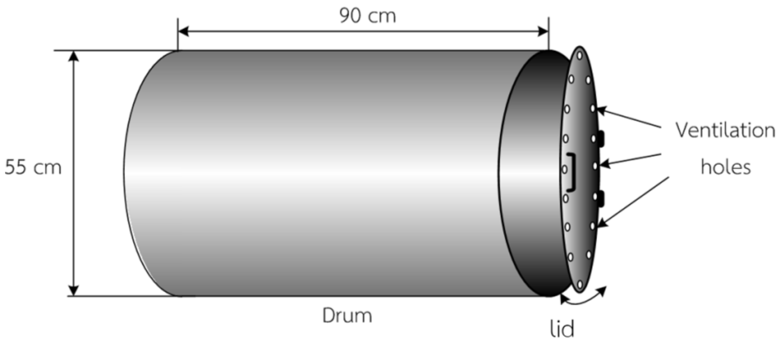



Figure 2.1. Rotary drum design with 200-litre of volume

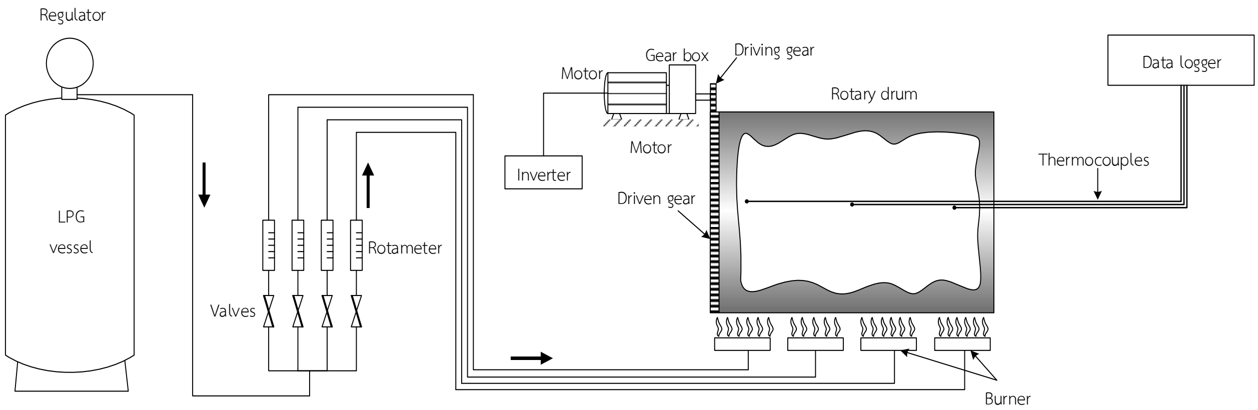



Figure 2.2. Diagram of rotary drum dryer (front view)

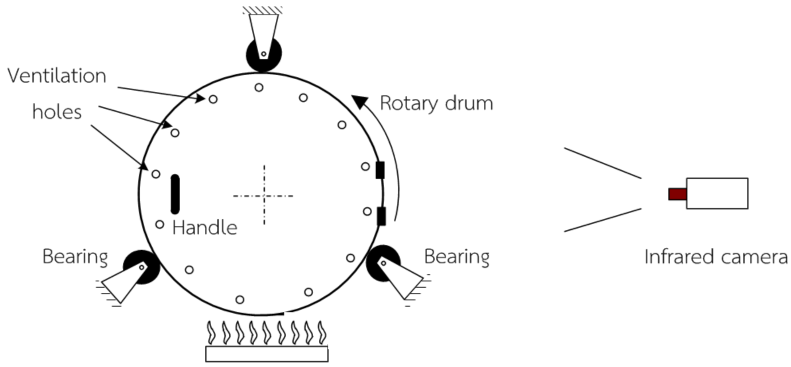
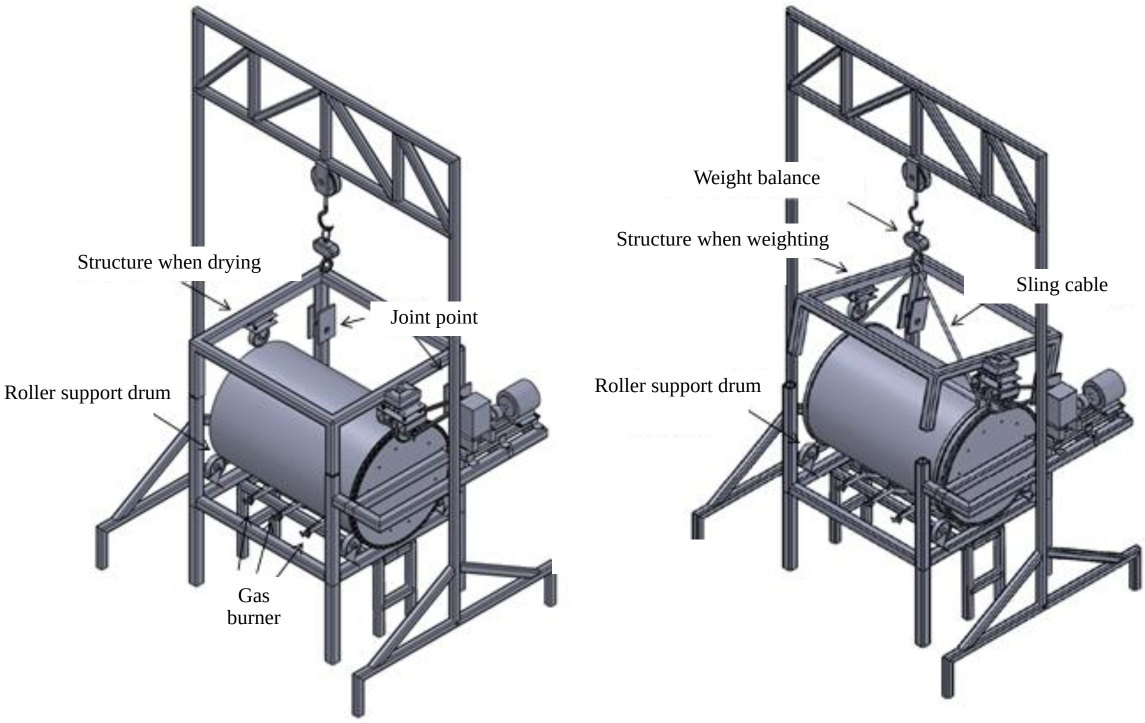



Figure 2.3. Diagram of rotary drum dryer (side view)

Figure 2.2. and 2.3. above show a diagram of the rotary drum system from a front and side view. The drum was supported by four bearings and was pressed by two rollers at the top. For number of ventilation holes were varied each side lid as 9, 18 and 36 holes. And then, rotation speed was varied to understand the sufficient speed in a specific range, namely 1.68, 4.14 and 8.34 rev/h. The rotation speed was controlled by the inverter.

To control heat transfer during experiment, LPG would be used as fuel to burn at the bottom of the drum as shown in Figure 2.3. Oil palm weight would be recorded periodically every hour during the experiment. After that, air temperature inside rotary drum would be measured using thermocouples as the average temperature inside rotary drum must be approximately 120$^{o}$C as shown in Figure 2.2. In addition, the temperature measured by each thermocouple could be used to compare with the temperature form CFD results. For temperature distribution on drum surface which were measured using IR camera would be used for setting up the boundary conditions in the simulation.

In rotary drum drying process, 50 kg of palm fruit was placed into the drum manually for every batch. The cap was closed after loading. For every 200 gram palm fruit was dried in the electric oven to evaluate the dried weight of palm fruit. During drying process, drum was weighted in every 1 hour time interval to evaluate moisture content of palm fruit (Figure 2.4.). After open joint point, sling cable was being used to make easier weighing process. The rotary drum was weight by using digital weight balance to record every weight change.

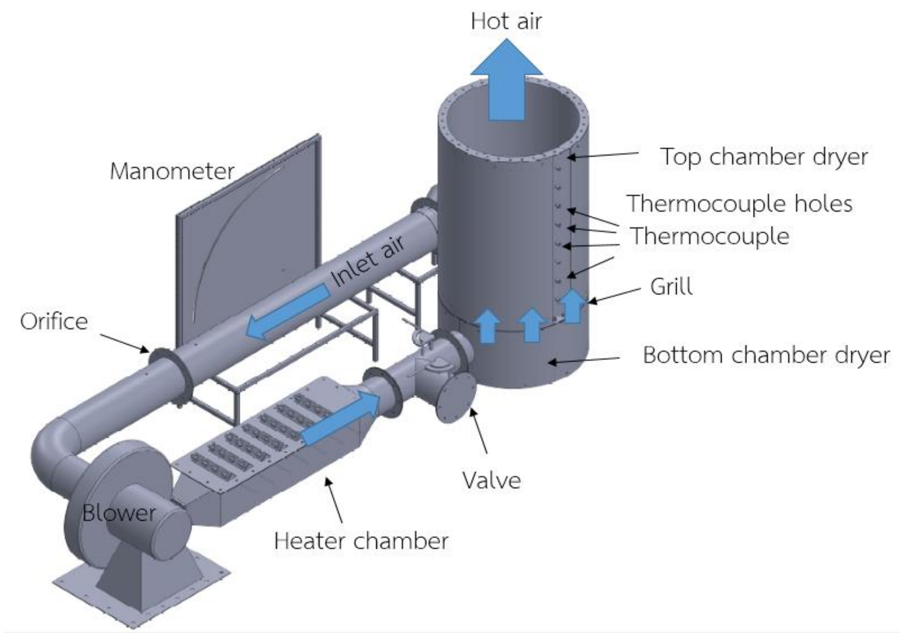



(a) During drying (b) During weighing

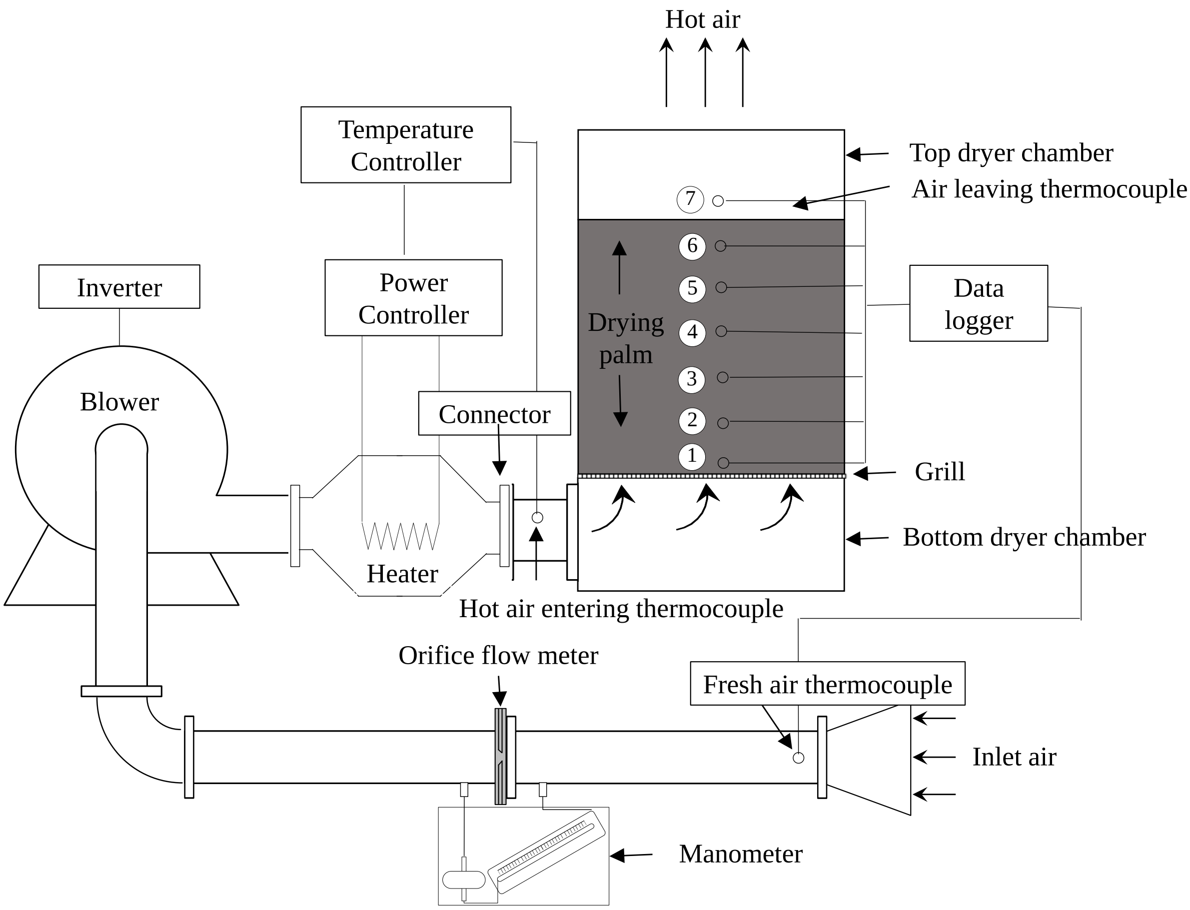
Figure 2.4. Rotary drum set up during research

## 2.2 Drying oil palm by comparing with conventional dryer

The drying characteristics of palm from rotary drum dryer would be compared to the conventional dryer. In model of conventional dryer imitated an industrial dryer was shown in Figure 2.5.(a) and (b). The air was sucked by blower through an orifice flow meter. The flow rate air was controlled by adjusting rotating speed of blower with an inverter. The air then flowed into heater chamber equipped with 16-kW heater. Then, for the velocity of hot air is 1 m/s and it was disperse to batch dryer. It was imitated factory velocity of hot air which it passes through to the palm layer. It was also controlled by a temperature controller and a power controller. The hot air entered into the bottom chamber dryer and passed through the grill and drying palm. The drying palm of 50 kg would be dried and would be weighed every hour.




(a) A model of conventional dryer




(b) Schematic of laboratory batch drier

Figure 2.5. Laboratory batch dryer

## 2.3 Evaluation of moisture content

A 200-gram sample of cooked defoliate oil palm fruit was placed in stainless tray and kept in an electric oven about 110$^{o}$C. The moisture content was determined using Eq. (1) (Pootao and Kanjanapongkul, 2016).

The weight of the sample at various times can be used to determine the moisture content,

$$\%\ MC(db) = \left(\frac{W - D}{D}\right) \times 100 \qquad (1)$$

where MC (db) is the dry-basis moisture content of cooked oil palm fruit (% dry-basis), W is the weight at every time weighting of dried palm fruit, and D is the dry weight of dried palm fruit.

In drying experiments, the initial moisture content of the palm fruits was recorded. In order to monitor the drying process, the moisture ratios were calculated which is derived from below as Eq. (2) (Pootao and Kanjanapongkul, 2016):

$$MR = \frac{(M_t - M_{eq})}{(M_{in} - M_{eq})} \qquad (2)$$

$M_t$ is the moisture content fresh oil palm fruit at every time (% dry-basis fraction), $M_{in}$ is the initial moisture content of the fresh oil palm fruit, dry-basis fraction (% dry-basis), and $M_{eq}$ is the equilibrium moisture content of dried palm fruit (% dry-basis). More details of this section have been written in publication as attached in **Appendix 2, 3, and 5**.

## 2.4 Evaluation of specific energy consumption and specific moisture evaporation rate of rotary dryer

In drying technology, there is a need to understand the specific energy consumption of rotary dryer comparing to batch dryer. The specific energy consumption was calculated based on following Eq. (3) (Motevali et al., 2011).

$$SEC = (E_f + E_e) / W_f \qquad (3)$$

where SEC is a specific energy consumption of drying oil palm (MJ/kg), $E_f$ is the fuel wood energy consumption during drying, that it covered weight of wood consumption multiple with heating value (MJ), $E_e$ is an electrical energy consumption during drying (MJ), and $W_f$ is final weight of oil palm after drying (kg dry-basis).

And also for the drying performances could be possible to calculated based on following Eq. (4) (Chou and Chua, 2006).

$$SMER = (E_f + E_e) / W_r / t_d \qquad (4)$$

SMER is specific moisture evaporation rate of drying oil palm (MJ/kg$_{(water\ removed)}$ /h, $W_r$ is the weight of water removed, that it covered initial weight of oil palm minus with final weight of oil palm (kg), and $t_d$ is drying time duration during drying (hour).

## 2.5 To study flow and heat transfer behaviour

The purpose of this study is to visualize flow and heat transfer behaviour of the rotating drum. In the designing process, the simulation of flow and heat transfer were performed using computer software ANSYS (Fluent). Figure 2.6. shows a model of rotary drum to simulate the flow and heat transfer. The model includes the surrounding air to observe hot air leaving from the drum to the surrounding when the drum would be heated.

The ambient air temperature would be set to equal ambient temperature of actual condition. The surface temperature of the rotary drum was set to be equal to the actual value which was measured by a thermal imaging camera during steady state of heating the drum. For the ventilation holes on the side, the rotary drum was designed with a pressure outlet, which allows the air to flow in or out according to the pressure and temperature changes in the rotary drum. The number of ventilation holes would be varied for double lid to 6, 8, 12 and 18 holes. The internal temperature of the air would increase due to the effect of the temperature on the drum. The volume of air inside the drum would increase. Then, hot air would flow through the ventilation holes. The boundary condition was set based on temperature measuring using infrared camera, and then the hot air would leave through the ventilation holes to surrounding. Therefore, the effect of holes number was designed to be appropriate to maintain the air temperature in the drum at a constant value of 120°C.

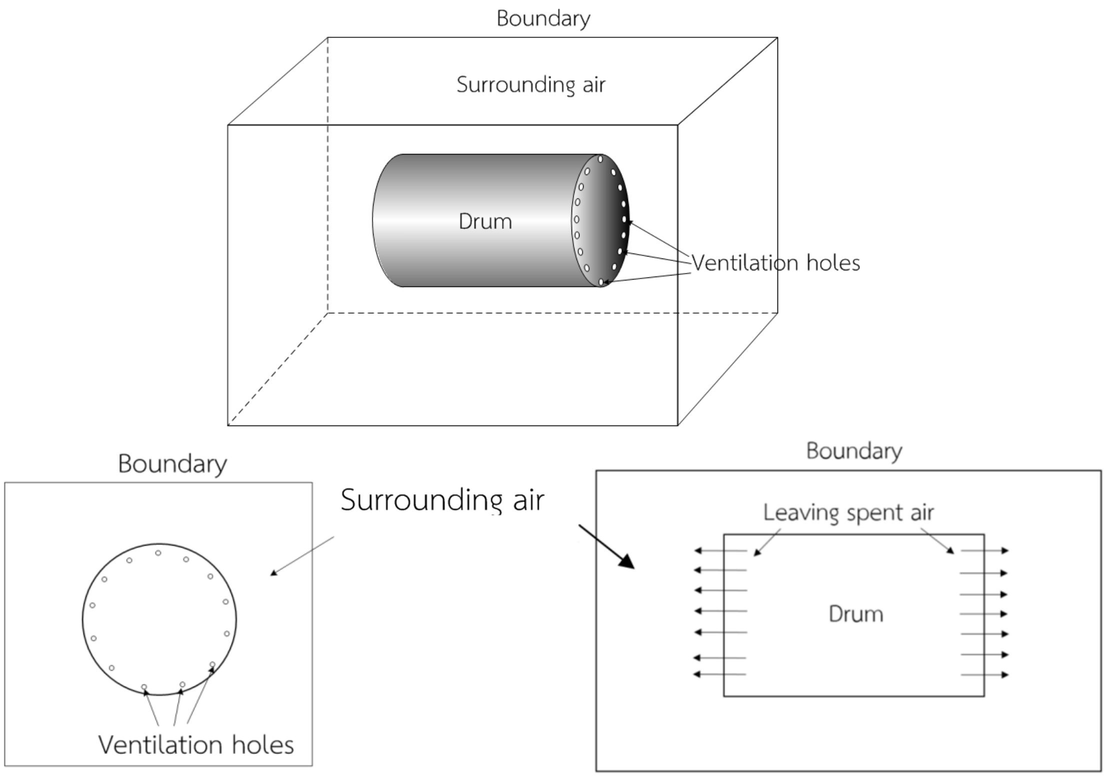



Figure 2.6. Model of rotary drum using 3D computer software

Figure 2.7. performs grid system of simulation domain. The variation elements in these simulation namely 0.27, 0.71, 1.20, and 1.57 million elements were examined. For the velocity of hot air from ventilation hole was analyzed. Furthermore, between 1.20 and 1.50 million elements showed the same trend. Therefore, 1.2 million was selected to be applied in this simulation (Figure 2.8.). More details of this section have been written in publication as attached in **Appendix 1 and 4**.

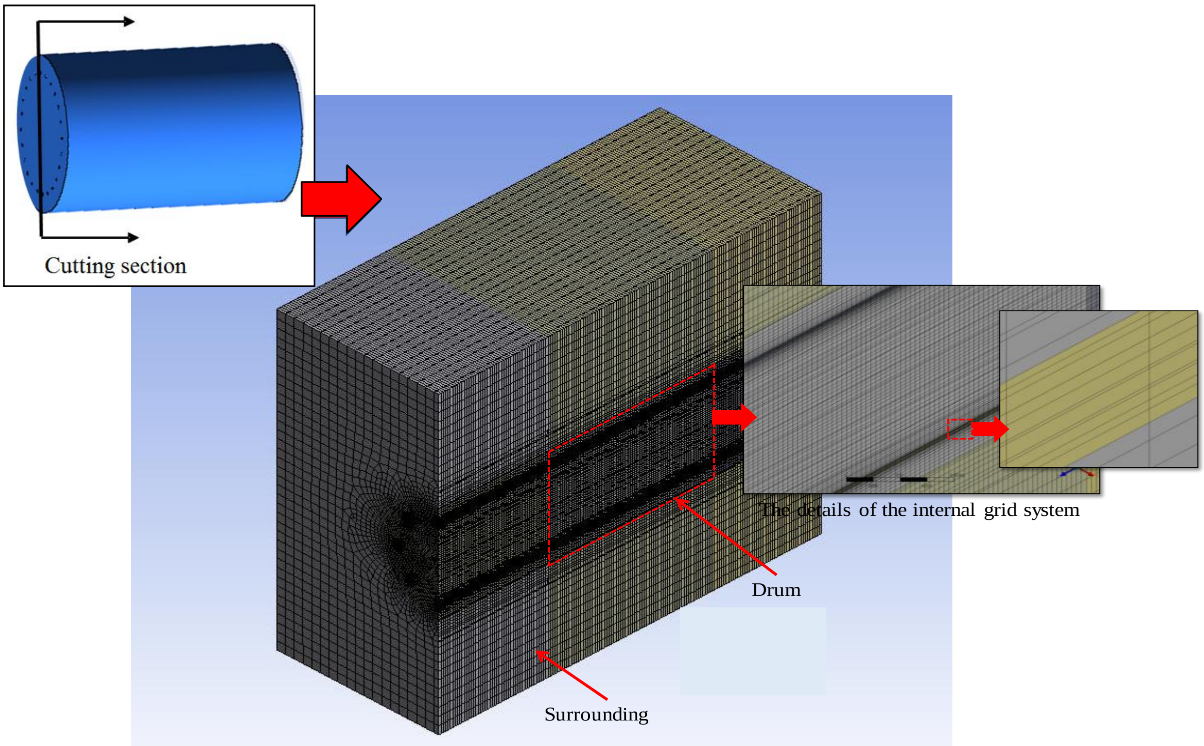



Figure 2.7. Half-cutting section grid of simulation domain

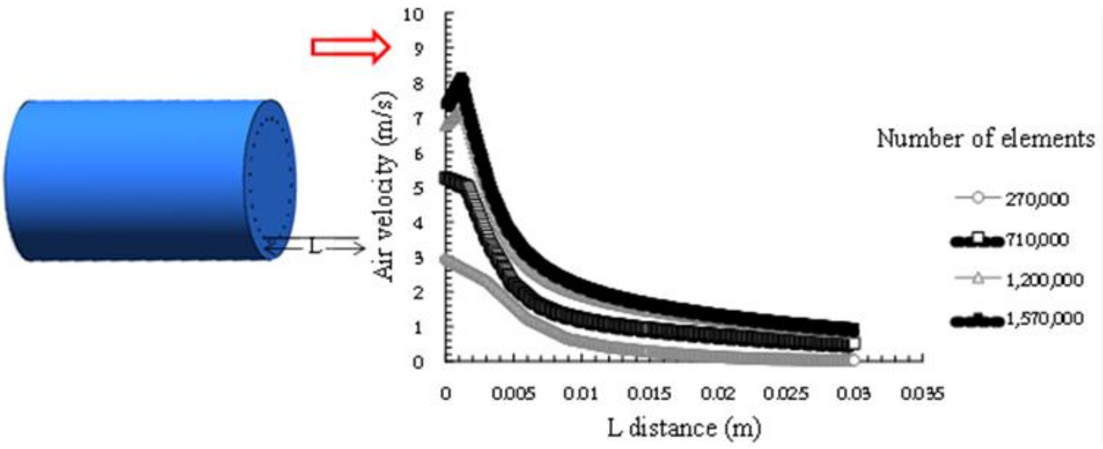



Figure 2.8. The effect of element numbers on air velocity of the centre of ventilation holes to the surrounding (L is the distance from ventilation hole to surrounding air)

# CHAPTER 3
# RESULTS AND DISCUSSIONS

## 3.1 Temperature variation of dried palm in a lab scale batch dryer

Figure 3.1. shows temperature changes during drying period of 26 hours. As shown in figure, the temperature was on 25$^{o}$C at starting point (marked as a). After 2 hours, temperature was increased due to hot air entering the chamber. Later on, the temperature varied according to position of each point (marked as c). Finally, the temperature was constant after drying period of 12 hours. For starting time at point 4 to 6 was increase gradually due to hot air slowly entered from bottom point (marked as e). Then, drying period of 8 hours for point 6 and 7 was the same (marked as f), because of contraction of palm fruit.

Figure 3.1. also represent dried palm appearance in each point, namely bottom layer for point 1 and 2, half height later for point 3 and 4, and top layer for point 5 and 6, respectively. From the figure, it shows that bottom layer performed cooked palm with colorless of kernel and brownish color of mesocarp (point 1 and 2). Different from half height layer and top layer, it represents uncooked dried palm with white spot of kernel and yellowish color of mesocarp. Since, moisture accumulation was more from bottom layer to the top layer of dried palm. More details of this section have been written in publication as attached in **Appendix 2**.

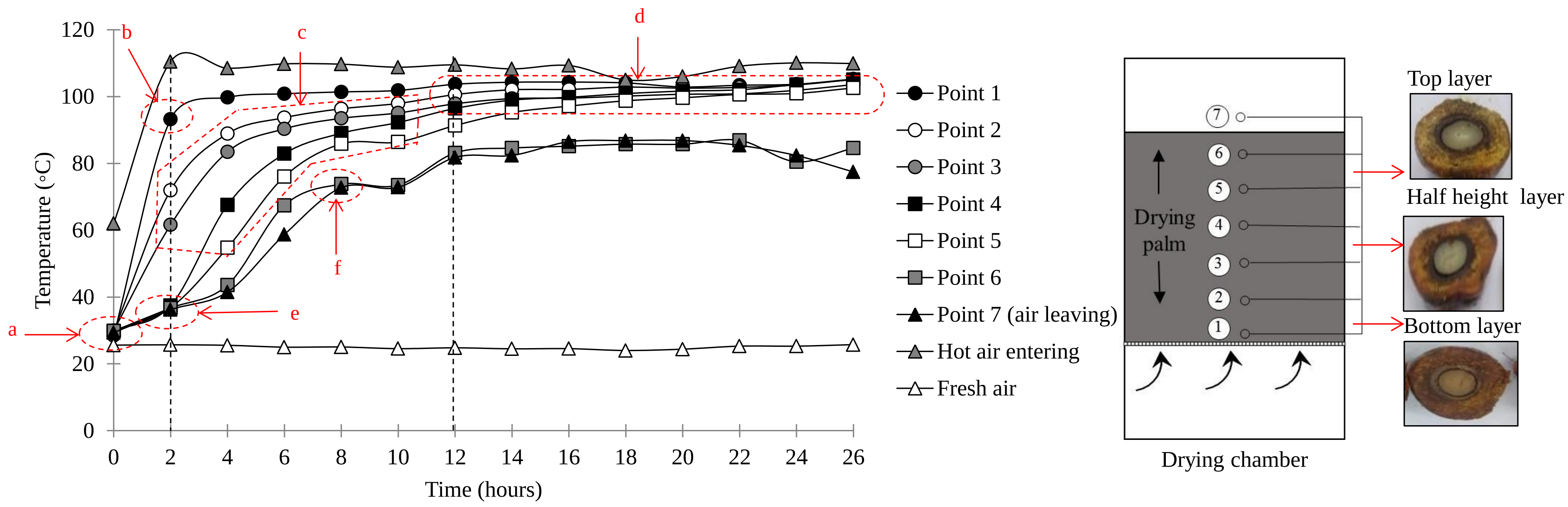
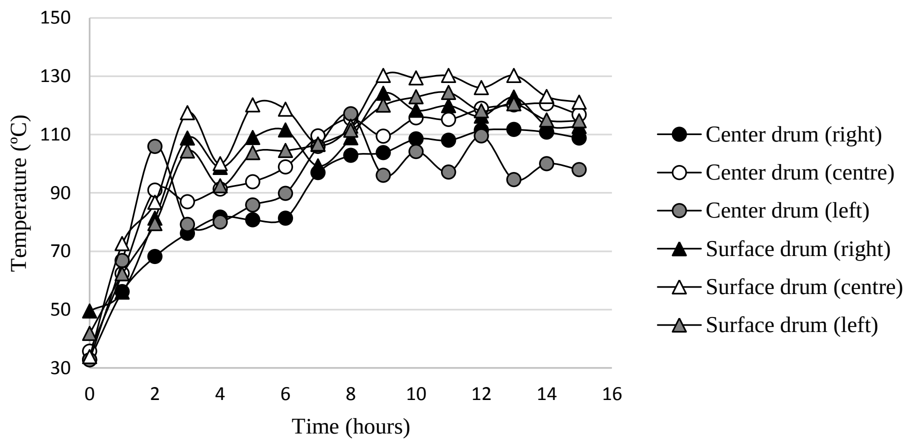



Figure 3.1. Temperature variation of dried palm in batch dryer (dried palm appearance from every layer at 26 hours drying period)

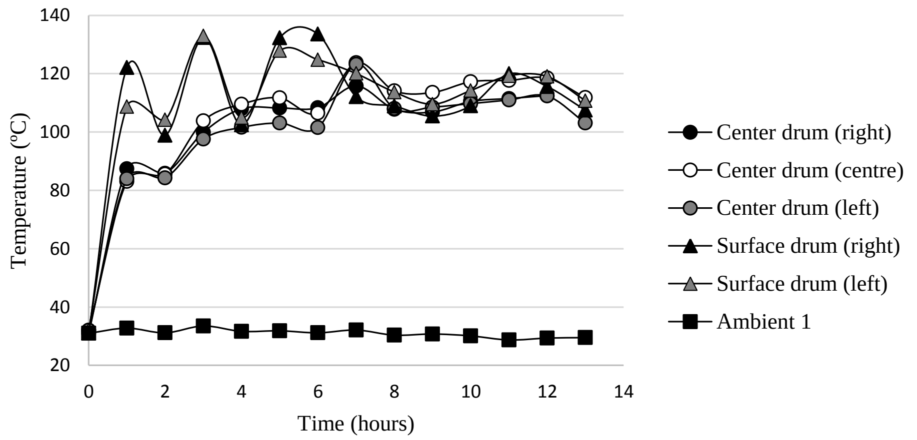
## 3.2 Temperature variation inside the rotary dryer

Figure 3.2. performs temperature variation inside the rotary dryer during drying at various rotating speed and ventilation hole. At first, trend of temperature shows small fluctuation due to system become steadier. Temperature of rotary dryer was increase immediately from initial at room temperature in the first two hours. It could be due to hot air slowly spreading inside rotary drum. After 4 hours, the temperature was increase immediately for case rotation speed of 8.34 and 4.14 rev/h. On the other hand, after 4 hours the temperature was decrease for case rotation speed of 1.68 rev/h. At bottom side, temperature was high because it is located near to the burner. It can be noted that temperature was fluctuated at ≈120$^{o}$C along drying time starting at 4 hours.

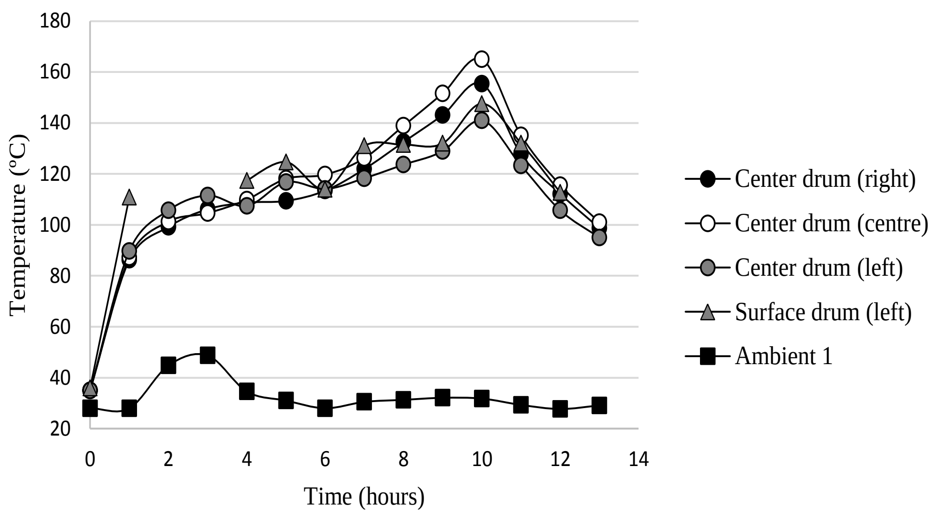
From the figure, it also shows that surface drum perform higher temperature than centre drum. It is due to temperature at bottom side was closed to the burner. Besides, it can be seen that at center side of rotary drum perform higher temperature comparing to right or left side of rotary drum. It happened due to accumulation of hot air in the center side of rotary drum.




(a) Rotating speed: 8.34 rev/h; Ventilation hole: 36 holes

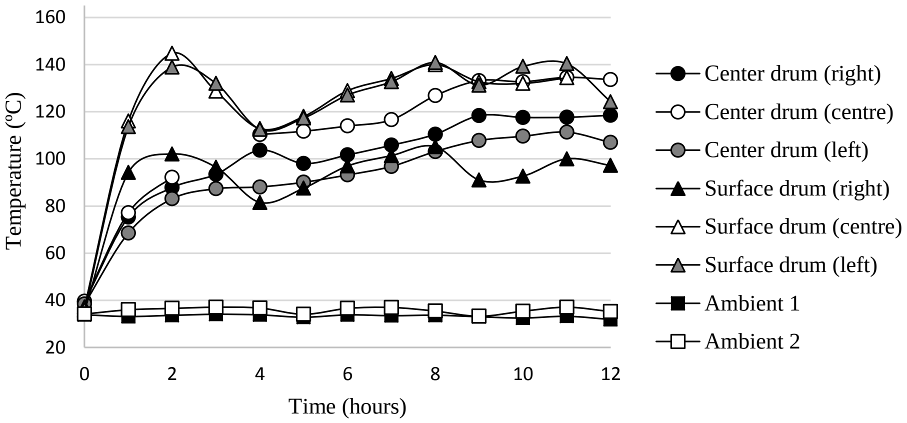



b) Rotating speed: 8.34 rev/h; Ventilation hole: 18 holes

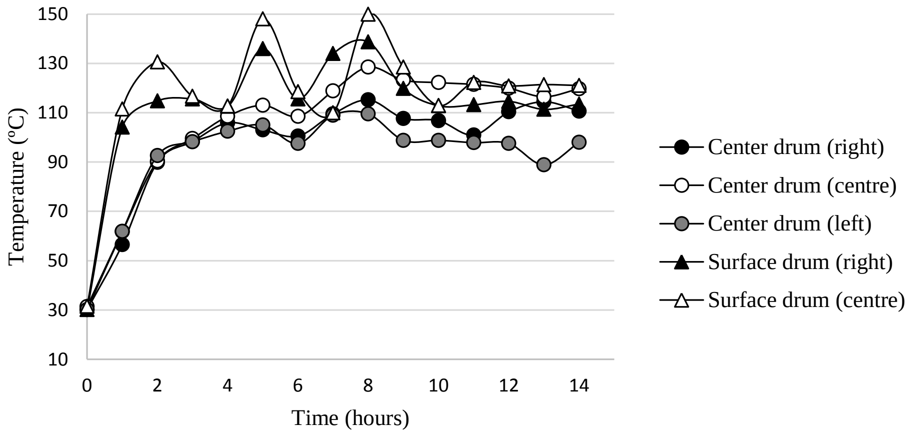



c) Rotating speed: 8.34 rev/h; Ventilation hole: 9 holes

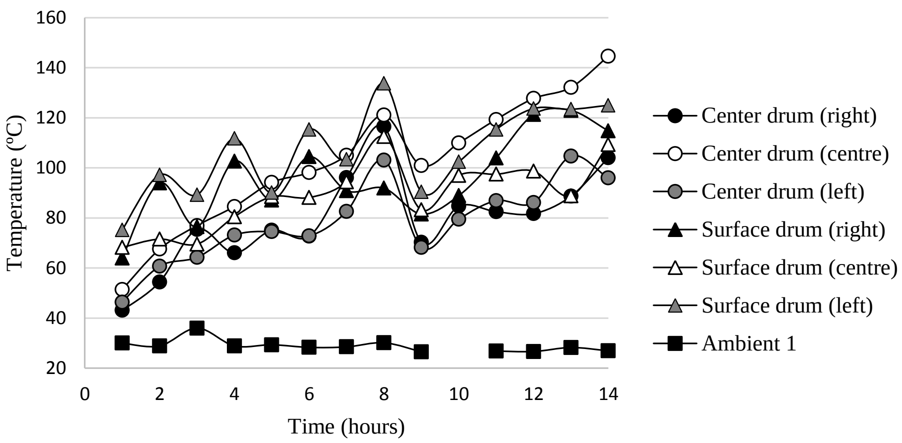
Figure 3.2. Temperature variation inside the rotary dryer




d) Rotating speed: 4.14 rev/h; Ventilation hole: 18 holes

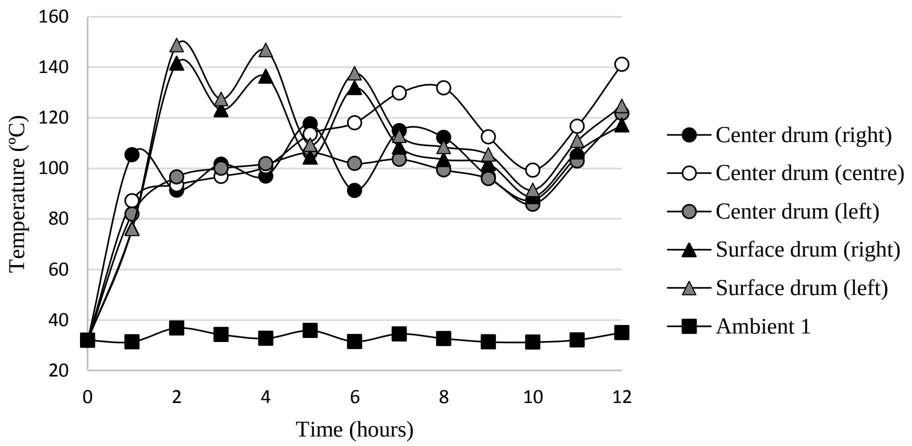



e) Rotating speed: 4.14 rev/h; Ventilation hole: 9 holes

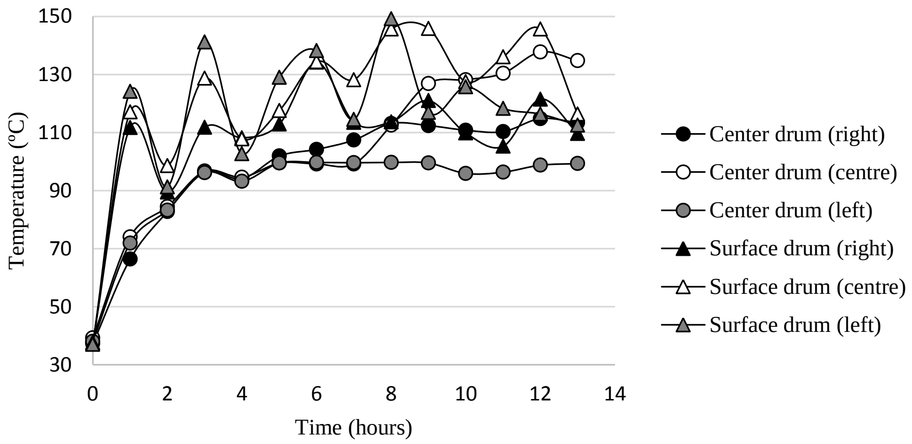



e) Rotating speed: 1.68 rev/h; Ventilation hole: 36 holes

Figure 3.2. Temperature variation inside the rotary dryer (continued)




e) Rotating speed: 1.68 rev/h; Ventilation hole: 18 holes




f) Rotating speed: 1.68 rev/h; Ventilation hole: 9 holes

Figure 3.2. Temperature variation inside the rotary dryer (continued)

### 3.3 Moisture ratio of dried palm from rotary dryer and conventional dryer

Figure 3.3. shows comparison moisture ratio of different rotation speed and ventilation holes of dried palm. From the figure, trend of moisture ratio is decreasing by the drying period. Moreover, there is small effect of rotation speed and ventilation hole of moisture ratio in each case. On the other hand, rotation speed of 8.34 rev/h with ventilation hole of 36 and rotation speed of 1.68 rev/h with ventilation hole of 36 showed higher value of moisture ratio compared to others. It happened due to accumulation of moisture content palm inside the drum. In the same way, batch drying process has longer time drying period. It might be due to accumulation of moisture content inside the batch chamber.

During 3 hours from beginning, for the experimental cases of rotary dryer performed slow decreasing trend compared to conventional batch dryer. It might be cause of moisture content from batch dryer could leave directly at the beginning, whereas for moisture from rotary dryer need to wait for heating up inside the drum. In addition, it took about 30 hours to reach dried palm with the same condition.

Figure 3.3. provides the result that large number of ventilation holes give higher result of moisture ratio comparing to small number of ventilation holes. A possible explanation for this result may be cause of moisture accumulation inside the rotary drum. Moreover, small number of ventilation holes gives lower results of moisture ratio. This result may be explained by the fact that moisture can easily leave the rotary drum.

Figure 3.3. also presents the results that higher rotation speed give higher result of moisture ratio comparing to lower rotation speed. Another possible explanation for this is that moisture accumulation inside the rotary drum. In addition, lower rotation speed gives lower results of moisture ratio. It seems possible that these results are due to moisture can easily leave the rotary drum. More details of this section have been written in publication as attached in **Appendix 3**.

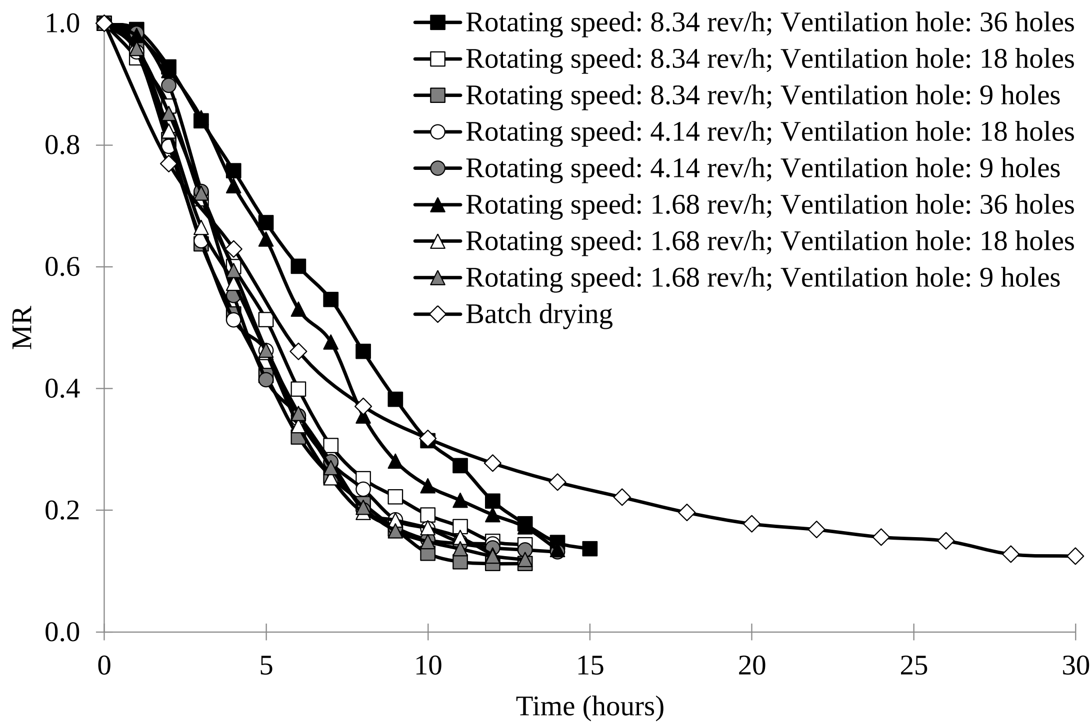



Figure 3.3. Moisture ratio of each cases

### 3.4 Energy consumption rate of rotary dryer

Figure 3.4. performs energy consumption rate with various rotation speed and ventilation hole during drying period. For rotation speed of 1.68 and 4.14 rev/h with ventilation hole of 9 and 18 showed similar trend of gas consumption in range of 0.60 to 0.68 $kg_{LPG}$ per hour. In these experimental cases, the highest energy consumption are for rotation speed of 8.34 rev/h with ventilation hole of 9 and ventilation hole of 4.14 rev/h with ventilation hole of 18 as 0.68 $kg_{LPG}$ per hour. Instead, for the lowest energy consumption are the case rotation speed of 1.68 rev/h with ventilation hole of 36 and rotation speed of 8.34 with ventilation hole of 36 as 0.49 $kg_{LPG}$ per hour.

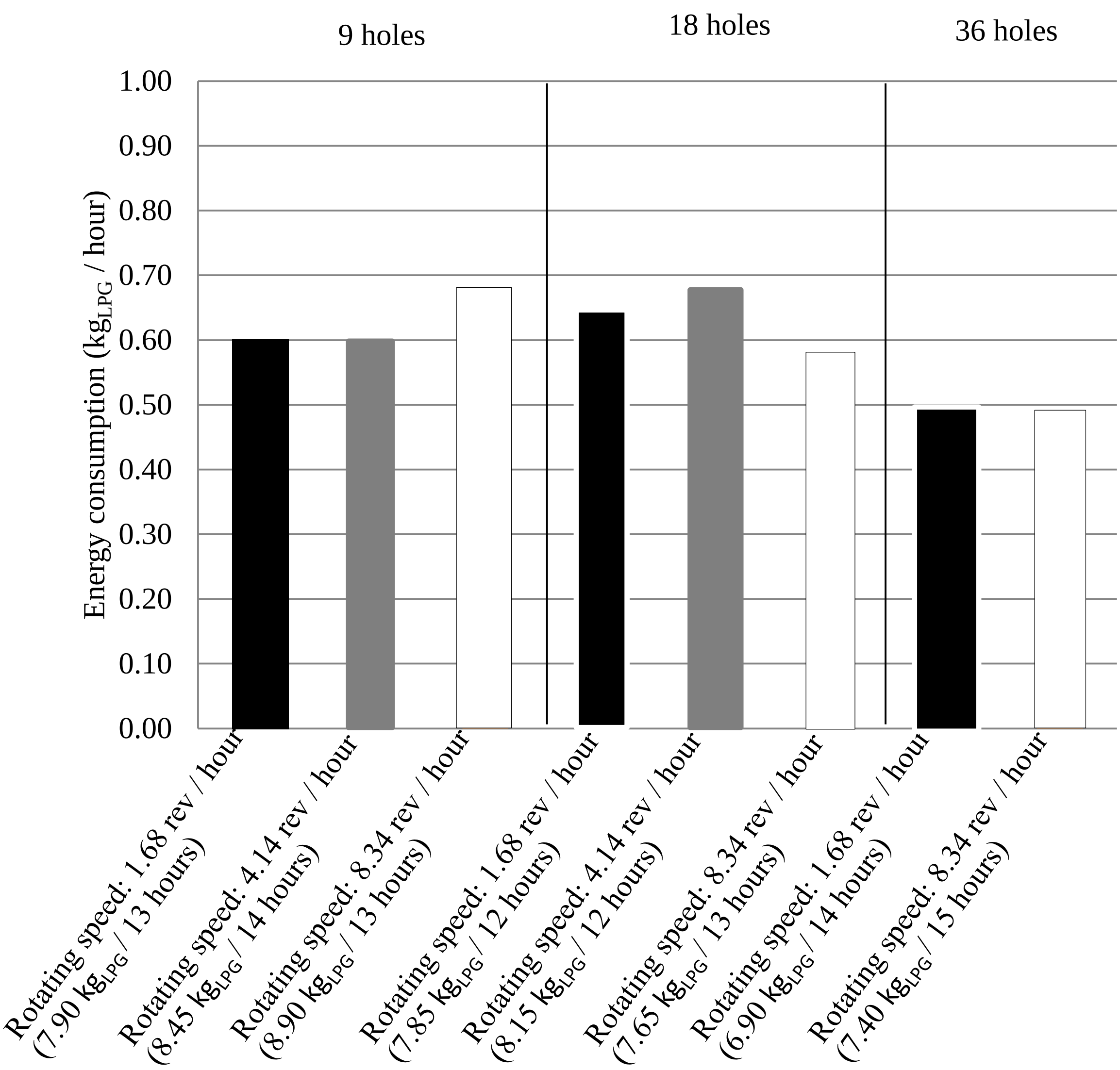



Figure 3.4. Energy consuming rate of various drying conditions

As shown in Figure 3.4., it performs the trend of energy consumption rate is increasing by the number of ventilation holes. This could be attributed to heat loss throughout the ventilation holes. On the contrary, higher number of ventilation holes provides lower energy consumption. Another possible explanation for this is that longer drying period could perform less heat loss during drying the rotary dryer.

Figure 3.4. also performs the results that higher rotation speed gives higher result of energy consumption of rotary dryer comparing to lower rotation speed. A possible explanation for this result may be due to heat loss during drying of the rotary drum. Besides, lower rotation speed gives lower results of energy consumption. Another possible explanation for this might be that these results are due to less heat loss during drying of the rotary drum. More details of this section have been written in publication as attached in **Appendix 3**.

## 3.5 Specific energy consumption of rotary dryer

Figure 3.5. represents specific energy consumption (SEC) for all cases conducted in the research. From this experiment, rotation speed of 1.68 rev/h and 4.14 rev/h with ventilation hole of 9 and 18 showed similar trend of specific energy consumption (SEC) in range of 8.229 to 8.861 $MJ/kg_{dried\ palm}$. For rotation speed of 8.34 rev/h with ventilation hole of 9 shows the highest specific energy consumption (SEC) value of 9.326 $MJ/kg_{dried\ palm}$. Whereas, batch drying presents the lowest specific energy consumption (SEC) value 4.496 $MJ/kg_{dried\ palm}$. It is because of drying duration of batch dryer compare to rotary dryer.

Figure 3.5. shows the same trend of specific energy consumption for various number of ventilation holes. However, higher number of ventilation holes with longer drying period provides lower result of specific energy consumption. This result may be explained by the fact that longer duration of drying could perform less energy consumption during drying period.

It also shows the trend of specific energy consumption is increasing by the rotation speed. Other possible explanation for this is that larger amount of energy usage in electrical motor in the rotary dryer. Additionally, lower rotation speed gives lower results of specific energy consumption. This could be attributed to smaller amount of energy usage in electrical motor in the rotary dryer.

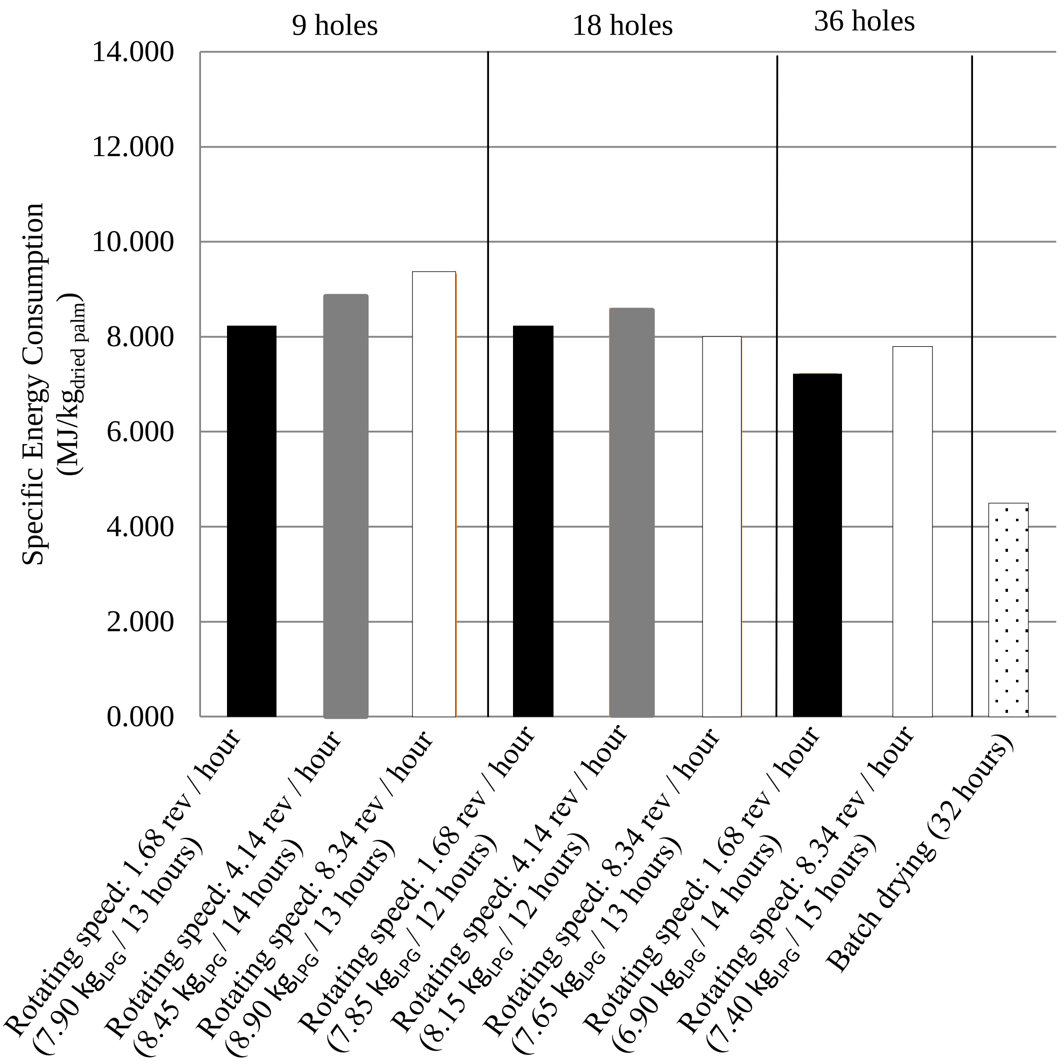



Figure 3.5. Specific energy consumption (SEC) in rotary dryer

## 3.6 Specific moisture evaporation rate of rotary dryer

Figure 3.6. shows specific moisture evaporation rate (SMER) for all cases in the experimental research. From the data, rotation speed of 1.68 and 4.14 rev/h shows similar trend of specific moisture evaporation rate (SMER) in range of 1.992 to 2.829 MJ/kg$_{\text{water removed}}$/hour. For rotation speed of 4.14 rev/h with ventilation hole of 18 represents the highest specific moisture evaporation rate (SMER) value of 2.829 MJ/kg$_{\text{water removed}}$/hour. And then, batch drying shows the lowest specific moisture evaporation rate (SMER) value of 0.501 MJ/kg$_{\text{water removed}}$/hour. It was due to lower moisture removal of batch drying comparing to rotary dryer.

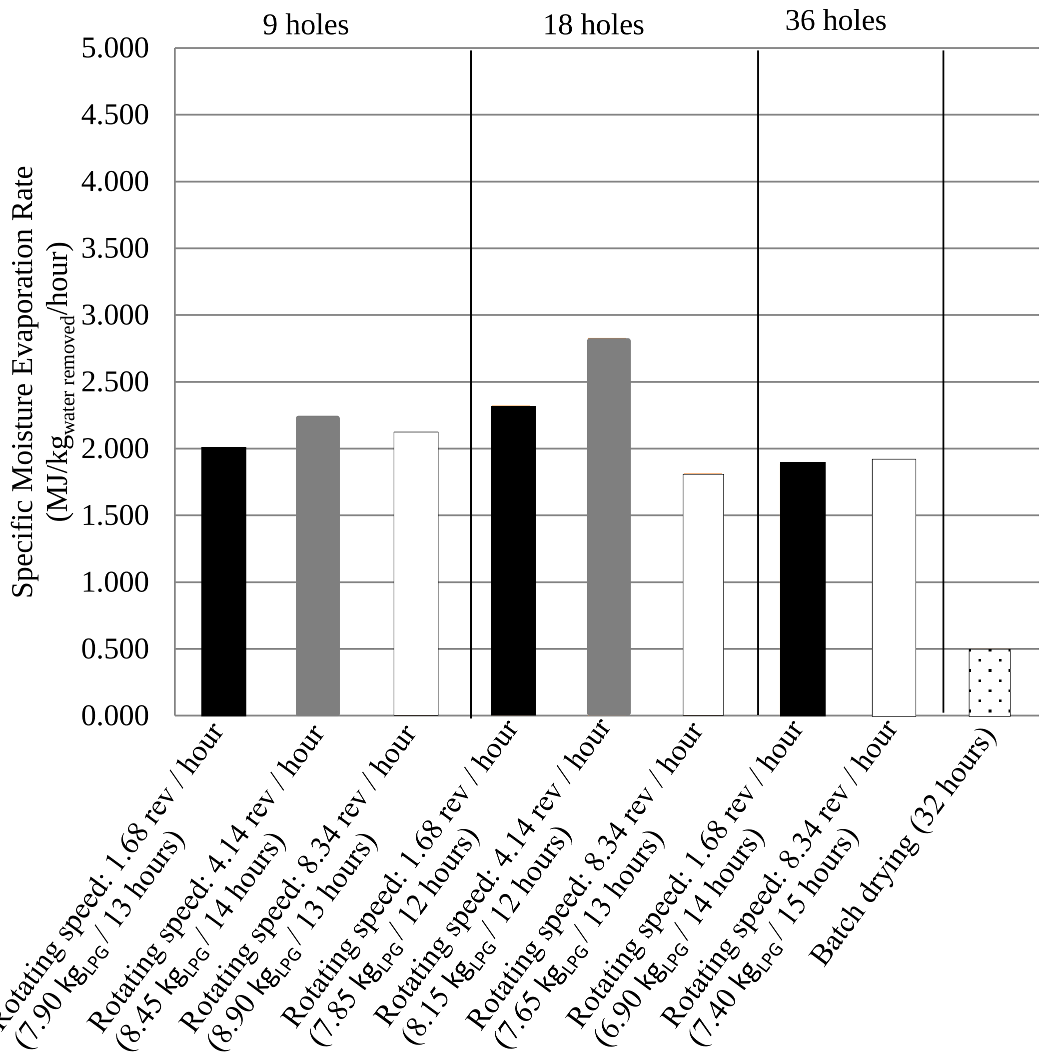


Figure 3.6. Specific moisture evaporation rate (SMER) in rotary dryer

Figure 3.6. provides the trend of specific moisture evaporation rate is increasing by the number of ventilation holes. A possible explanation for this result may be due to less moisture content of dried palm. However, higher ventilation holes number shows lower value of specific moisture evaporation rate. A possible explanation by the fact is that longer drying period could possibly effect on moisture content of dried palm.

It also shows the trend of specific moisture evaporation rate is increasing by the rotation speed. There is other possible explanation for this is that less value of moisture content. Besides, lower rotation speed gives lower results of specific moisture evaporation rate. Other possible explanation for this might be that these results are due to accumulation of moisture content after drying.

### 3.7 Visual appearance of dried palm in rotary dryer

Figure 3.7. represents visual appearance of dried palm at rotation speed of 8.34 rev/h with ventilation hole of 36 and rotation speed of 1.68 rev/h with ventilation hole of 36. Figure 3.7.a at 7 and 8 hours drying period shows uncooked palm with white color of kernel and yellowish of mesocarp. Besides, for 9 and 10 hours drying period result in white spot of kernel and brownish of mesocarp. However, Figure 3.7.b at 9 hours drying period represents cook palm with colorless of kernel and brownish of mesocarp.


7 hours


8 hours


9 hours


10 hours

(a) Rotation speed of 8.34 rev/h with ventilation hole of 36 holes for 7, 8, 9 and 10 hours of drying period


8 hours


9 hours

(b) Rotation speed of 1,68 rev/h with ventilation holes of 36 for 8 and 9 hours of drying period

Figure 3.7. Visual appearance of dried palm

Figure 3.7. provides the results that higher rotation speed performs uncooked palm comparing to lower rotation speed. It seems possible that these results are due to hot air fast spreading into the dried palm. Moreover, lower rotation speed shows cooked palm. A possible explanation for this might be that these results are due

to hot air spreading slowly into the dried palm. More details of this section have been written in publication as attached in **Appendix 3**.

## 3.8 FFA percentage and oil yield of dried palm

Figure 3.8. represent the percentage FFA content of dried palm comparing between rotary dryer with batch dryer. From the figure, it resulted 11.27% and 5.40% for rotary dryer and batch dryer, respectively. Based on standard of FFA percentage have to reach not more than 5%. The percentage of FFA represents the purities of Crude Palm Oil (CPO) of dried palm. Otherwise, it can be used for other purpose as animal food.

Figure 3.8. also performs oil yield of rotary dryer and batch dryer. From the figure, oil yield of rotary dryer and batch dryer shows the same trend with percentage of FFA. Oil yield of rotary dryer is higher than batch dryer as 68.6 gram and 58.7, respectively. In general, it might be cause of homogenize dried palm during drying process by using rotary dryer. More details of this section have been written in publication as attached in **Appendix 3**.

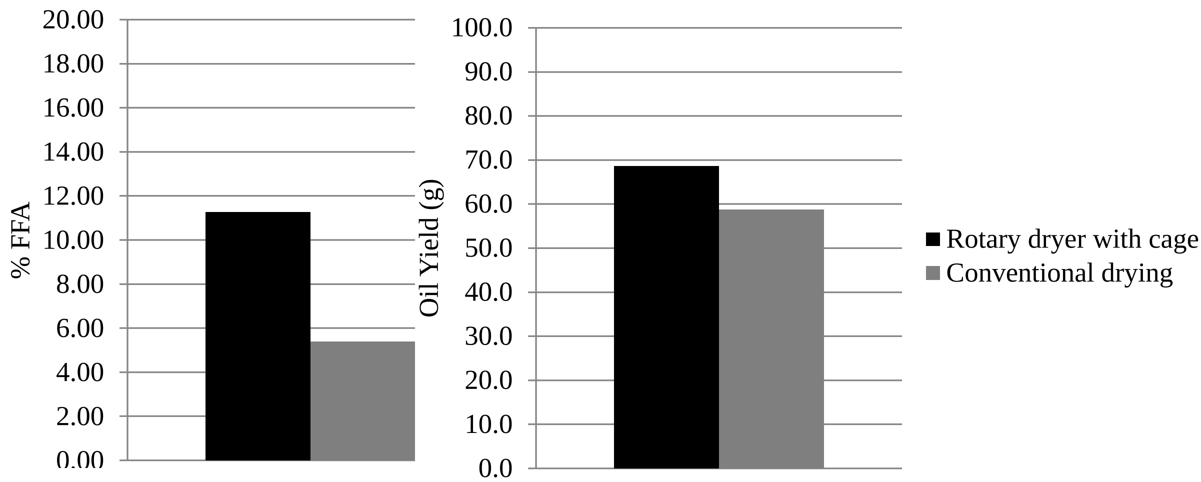



Figure 3.8. FFA percentage and oil yield of dried palm

# CHAPTER 4
# CONCLUSIONS

## 4.1 Conclusions

This research studied about effect the rotation speeds and ventilation holes of rotary drum dryer on moisture ratio, energy consumption and CPO quality (FFA and quantities) comparing to conventional batch drier, respectively. Based on this study, rotation speeds and ventilation holes give small effect of moisture ratio in every experimental cases. For fuel consumption, rotation speed of 1.68 rev/h with ventilation holes of 36 and rotation speed of 8.34 rev/h with ventilation holes of 36 represent the lowest fuel consumption of 0.49 $kg_{LPG}$ per hour. For specific energy consumption value, rotation speed of 8.34 rev/h with ventilation hole of 9 shows the highest specific energy consumption (SEC) value of 9.326 $MJ/kg_{dried\ palm}$. Whereas, batch drying presents the lowest specific energy consumption (SEC) value 4.496 $MJ/kg_{dried\ palm}$. Moreover, for specific moisture evaporation rate value, rotation speed of 4.14 rev/h with ventilation hole of 18 represents the highest specific moisture evaporation rate (SMER) value of 2.829 $MJ/kg_{water\ removed}$/hour. And then, batch drying shows the lowest specific moisture evaporation rate (SMER) value of 0.501 $MJ/kg_{water\ removed}$/hour. For dried palm quality of rotary dryer, rotation speed of 1.68 rev/h with ventilation hole of 36 drying period of 9 hours perform cook dried palm. At the same time, for dried palm quality of batch dryer bottom layer performed cooked palm with colorless of kernel and brownish color of mesocarp. Second, FFA percentage of rotary drum dryer has higher value than batch dryer. After that, for rotary drum dryer give higher value of oil yield rather than batch dryer. Besides, the advantages of rotary dryer provide homogenous dried palm. In factory, the drying process take time about 30 - 40 hours to achieved good condition of dried palm. For the simulation result, ventilation hole were studied at various holes namely, 6, 8, 12 and 18 holes. Moreover, at 1,400 and 1,600 seconds for 12 ventilation holes showed the uniform temperature distribution, respectively.

### 4.2 Suggestions

In this research, the temperature used in the experiment is 120$^{o}$C. Anyway, it is possible to create different temperature variation that is shorter in drying period. Hence, the cooked palm fruit could be possible compare to the cooked palm in the industry.

### 4.3 Future works

In order to improve rotary drier efficiency, the velocity flow and temperature distribution with different ventilation hole and temperature variation might be performs higher efficiency drying pattern to be adopt in lab scale experiment. Moreover, industrial scale could be considered as an alternative drying technology in oil palm industry. In the future work, energy cost for both lab scale and industrial case are the issues that worth to investigate.

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# APPENDICES

**APPENDIX 1**

The effect of ventilation hole on flow behaviour and heat transfer of rotary drum dryer

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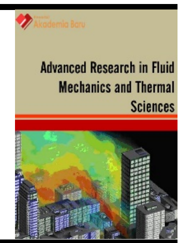


# The Effect of Ventilation Hole Number on Flow Behavior and Heat Transfer of Rotary Drum Dryer

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**ABSTRACT**

The effect of ventilation holes on flow behavior and heat transfer of rotary drum dryer were studied by using Computational Fluid Dynamics (CFD). In the experimental apparatus, the drum was heated by direct burning with flame from LPG at the bottom surface of the drum. In steady state condition, the temperature distribution on the surface of the drum was detected by using infrared camera. The average temperature on the cap surface was 80ºC, the drum surface was 130ºC, and the temperature inside rotary drum was 120ºC. In order to maintain the air temperature inside the drum at 120ºC, the number of ventilation holes was varied by using CFD. In the 3-D numerical model of the drum including ambient air was simulated in transient. The ventilation holes were drilled on the drum caps, and the number of the hole on each cap was varied at 6, 8, 12, and 18 holes. The results showed that the air temperature inside the drum at the condition of ≥12 holes was the highest with the shortest time. The longest time of 1,400 seconds and 1,600 seconds were observed to be uniform temperature and uniform velocity flow in this research.



## 1. Introduction

Drying is the process removal of moisture by transferring heat that can change the quality of product [1]. In this process, heat is transferred from the hot dry air to the product, before evaporating the moisture of the surface material. There are two sequential processes when moisture material undergoes thermal drying [1]. For the first process, removal of water as vapour from the surface material depends on outside condition, temperature, air moisture and flow, and surface area exposed. For the second process is removal of moisture as function of natural physical from solid temperature. Inside the drying operation, this process can be limited by drying rate factor, although this happen simultaneously throughout the drying cycle.

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Nowadays, rotary drum drying was being developed because of the uniformity of material being dried inside the rotary drum [2-4]. Some of experts have developed to study about flow behaviour for continuous rotary drum [5-8]. Alonso *et al.,* [9] also reported that rotary drum in solar thermal application give positive effects such as good mixing and homogeneous distribution of temperature inside the chamber.

Previous study has been conducted by Delele *et al.,* [10] about rotary drum speed, feed rate and drum angle that showed strong effect of particle and fluid flow behaviors inside rotary drum. Santos *et al.,* [11] also investigate particle size and density differences that could affect physically in the rotary drum. Machado *et al.,* [12] reported rotary drum with different rotation speed, while Liu *et al.,* [13] investigated liquid gas particle in a rotary drum that showed not clear effect on gas improvement and particle mixing in the process.

In rotary drum drying technique, simulation particle need to be considered such as moisture content of solid, air distribution and temperature inside the drum. Some researchers has reported about simulation particle, Geng *et al.,* [14] and Geng *et al.,* [15] reported about particle transport the axial direction of drum and transverse direction of drum. Gu *et al.,* [16] and Gu *et al.,* [17] investigated about particle and gas flow behaviour in rotary drum. Geng *et al.,* [18] studied about particle motion of rotary drum dyer. Karunarathne *et al.,* [19] and Santos *et al.,* [11] reported about particle behaviour with different size and density differences for rotary drum dryer. Furthermore, Nafsun *et al.,* [20] also reported about particle size to thermal mixing behavior, therefore no reported about design rotary drum dryer with ventilation hole as wet warm air removal.

In this study, a rotary drum dryer was designed with varying ventilation holes. The model of rotary drum dryer is shown in Figure 1. Burners were located at the bottom of the drum for heating. The wet warm air passed through the ventilation hole. In the previous of our work, the study of laboratory experiment palm fruit drying by using a newly-designed of rotary drum dryer have been done [21]. As well as, preliminary study of flow behaviour and heat transfer of the drum dryer was simulated by using CFD [22]. CFD was used by many fields for example in industrial device [23], fossil fuel [24], solar energy [25], gas turbine [26], and some in biomedical field [27]. In this work, the effect of ventilation hole number on flow behaviour and heat transfer of rotary drum dryer were studied by using Computational Fluid Dynamics (CFD).

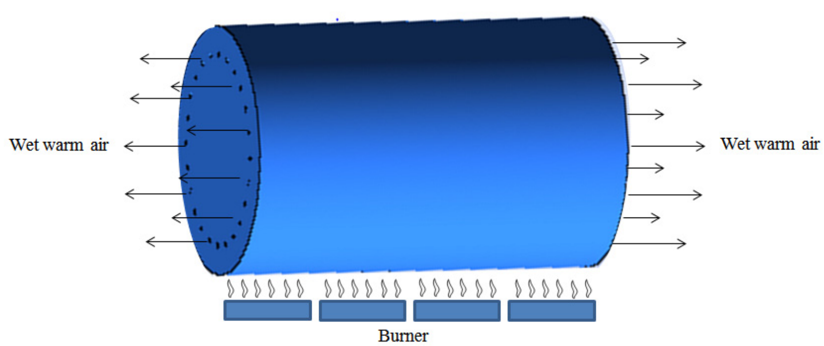



**Fig. 1.** Newly-designed of rotary drum dryer

## 2. Methodology

### *2.1 Rotary Drum Dryer*

The design of rotary drum dryer was built up with metal sheet with thickness of 3 mm. For the dimension was fabricated with 90 cm in length and 57.5 cm in diameter. The rotary drum has roller that was rotated as function with gear and electrical motor. Later on, the rotary drum was heated by

4 burners at the bottom of the drum using LPG as a fuel source. The details of the rotary drum were in our previous work [21].

As shown in Figure 2 and Figure 3, the temperature on the surface of rotary drum and on the cap were captured with steady state condition using infrared camera. The drying process temperature in rotary drum was averaged as 80°C of cap temperature, 130°C of drum surface temperature and 120°C of the air temperature at the center of rotary drum. At this point, the drying process of rotary drum dryer was heated with LPG by applying direct contact to the bottom of the drum. The rotation speed of the rotary drum was slowly at 1.68 rev/hour, 4.14 rev/hour, and 8.34 rev/hour.

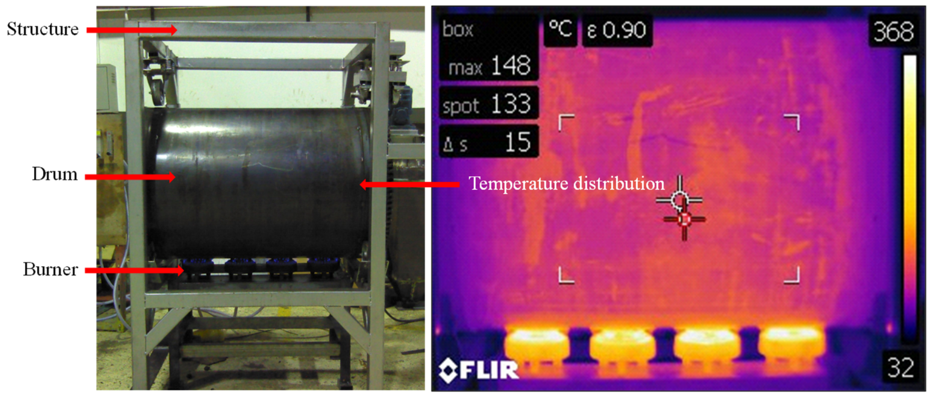



**Fig. 2.** Left: Photo of rotary drum, and Right: Temperature distribution of rotary drum

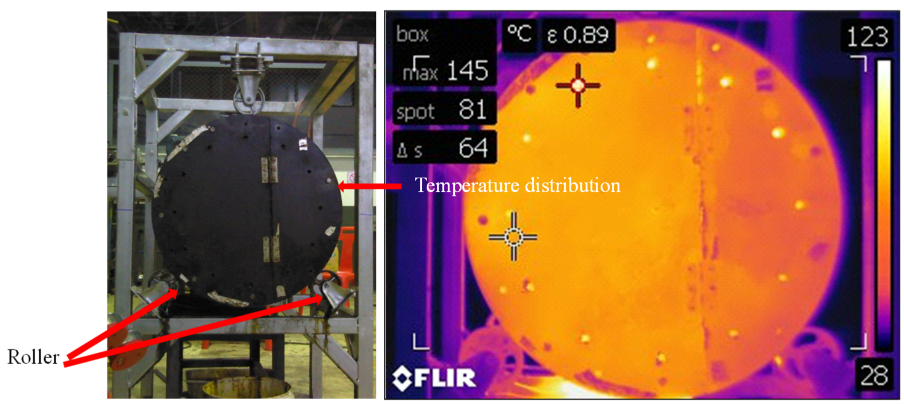



**Fig. 3.** Left: Photo of surface cap, and Right: Temperature distribution of surface cap

### *2.2 Design of Simulation and Grid*

In this simulation work, ANSYS Fluent version 15.0 was used to simulate the flow characteristic and heat transfer of rotary drum dryer. A 3−D with finite volume method was applied to solve governing equation as boundary condition of rotary drum. In order to minimize the calculation task, the size of numerical model was created with decreasing proportionally 10 times smaller than the real drum. The 3-D numerical model of the drum including ambient air is shown in Figure 4.

The grid system of the numerical domain is shown in Figure 5. In cutting section was observed and appeared internal grid system. The geometries of elements were rectangular shape. In order to evaluate saturated element number, the variation of element number at 0.27, 0.71, 1.20, and 1.57 million elements were examined. The flow velocity of hot air discharging from ventilation hole at variant element number is shown in Figure 6. It showed that the trend of velocity was higher when the element number became larger. For the case of 1.20 and 1.57 million elements, the trend of velocity was almost the same. Therefore, 1.2 million cases were being used to be applied in this simulation.

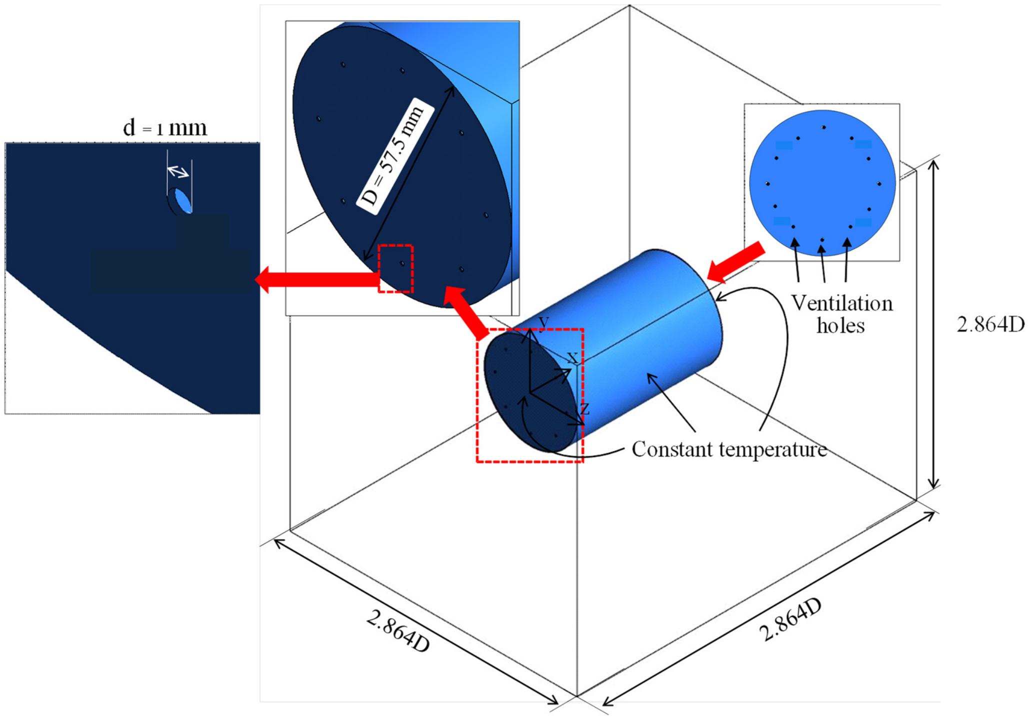



**Fig. 4.** Rotary drum dryer model and surrounding (minimizing proportionally 10 times respecting the actual size of experimental drum)

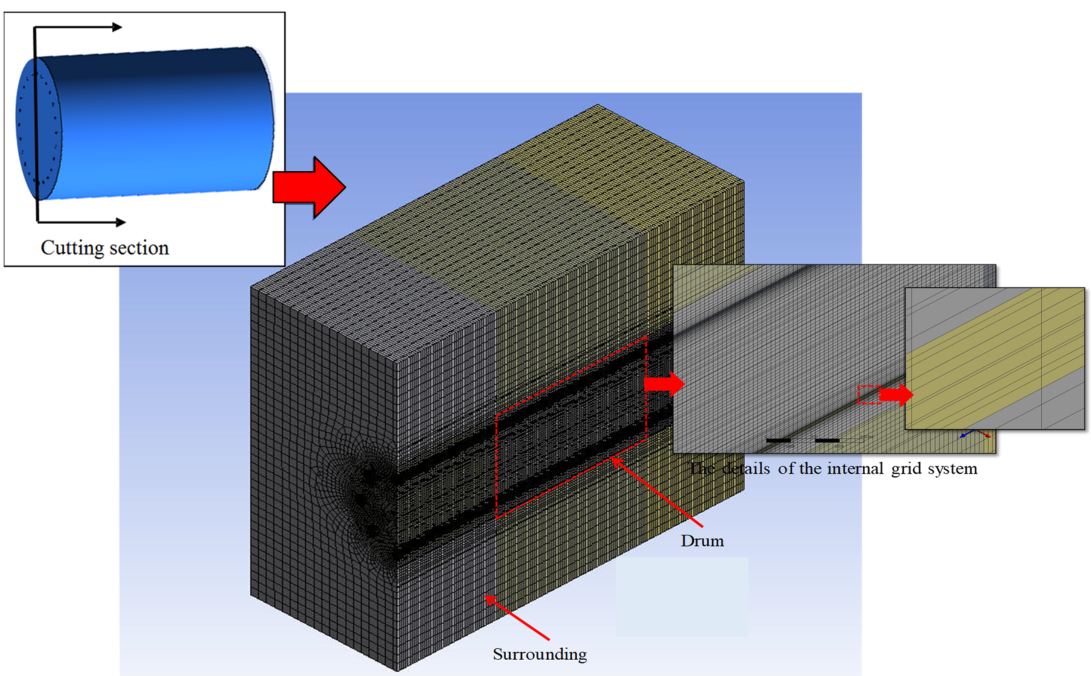



**Fig. 5.** Internal grid of the simulation domain

For the boundary condition of numerical domain was applied with similarity of experimental rotary drum. The details of the boundary conditions were shown in Table 1.

**Table 1**
Boundary condition of rotary drum dryer

| Conditions | Setting |
|---|---|
| The temperature of drum dryer | 130 °C |
| The temperature of drum dryer cap | 80 °C |
| The temperature of environment | 29 °C |
| Ventilation holes | Pressure outlet |
| Outer surface of surrounding air | Pressure outlet |

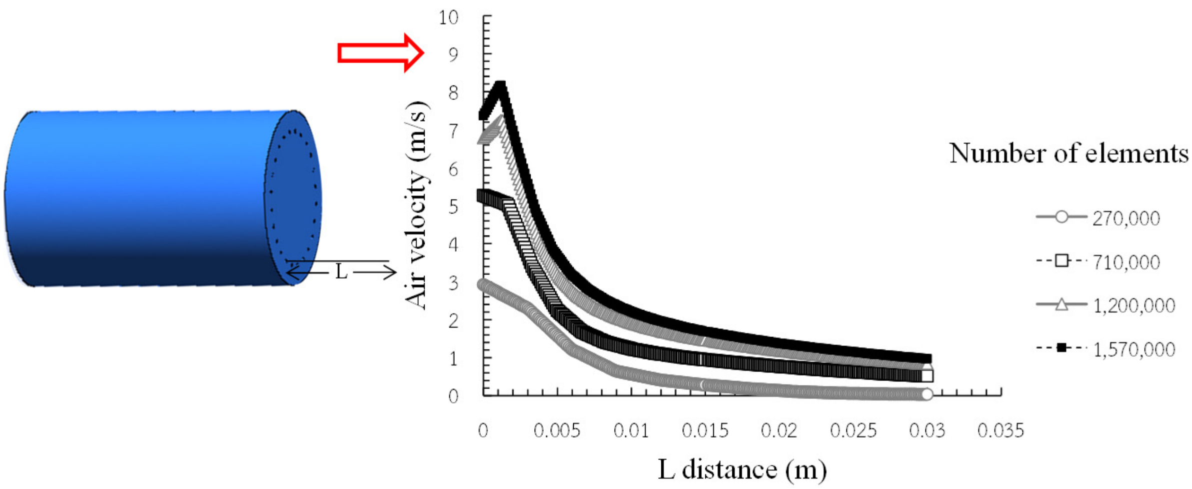



**Fig. 6.** The effect of element numbers on air velocity of the centre of ventilation holes to the surrounding (L is the distance from ventilation hole to surrounding air)

*2.3 Simulation Assumption*

To simplify numerical simulation, the empty drum was heated without drying material, and the drum was no rotation due to very slow rotating speed (1.68 rev/hour) for the test case (the case of capturing temperature on the surface). The heat from high temperature on the surface of the drum and the caps transferred to the air inside the drum. Therefore, the calculation was considered under unsteady state. The gravity effect was applied, and incompressible flow was considered.

*2.4 Calculation Method*

The solution in this simulation was evaluated with SIMPLE algorithm and a second order upwind for all spatial discretization. It was considered in transient condition, and then operated until the temperature at the center of drum become consistent. The solution was considered to be converged when the normalized residual of the algebraic equations were less than a prescribe value of 1.0 x $10^{-4}$.

## 3. Results and Discussions

The criteria for identifying optimal hole numbers for designing the rotary drum dryer, the temperature of air at the center of the drum were considered for getting high temperature in the shortest heating period. The air temperature at the center of rotary drum varying with hole simulation is shown in Figure 7. The increasing of the air temperature at the center of drum depended on time in the range of <1,200 seconds. The air temperature at the center of drum became steady state at time <1,200 seconds, approximately. At 6 holes, the increasing of air temperature at the center of drum was faster than those other cases, but at steady state (time <1,200 seconds), its temperature was lower than those other cases. From the figure, it showed that the temperatures at the center of drum for the case of 12 and 18 holes were the highest. As a result of experimental case of 18 holes was the temperature with time at the centre of rotary drum. The temperature was rapidly increased until <2,400 seconds of drying period. The temperature distribution at the centre of drum become almost steady after <2,400 seconds of drying period. Thus, the period of the temperature at the drum centre becoming steady is longer compared with other CFD cases. It was due to effect of heat losses from radiation and natural convection in the experiment.

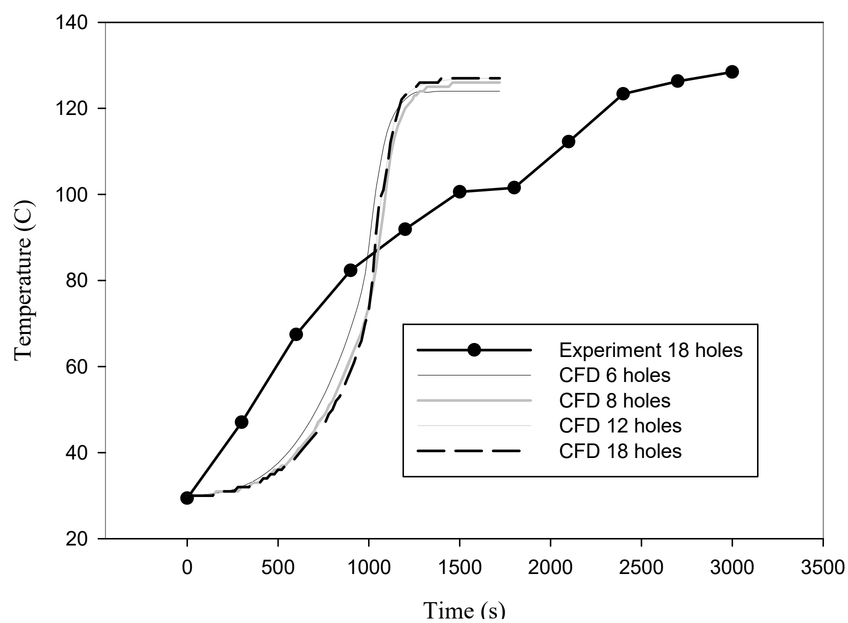



**Fig. 7.** Temperature with time at the centre of rotary drum varying with time

The temperature along the centerline at the middle drum in various ventilation hole are shown in Figure 8. At first, the lower temperature in rotary drum was observed with 6 ventilation hole number. The higher temperature of middle drum increased when the number of ventilation hole is larger. At this point, the temperature along the centerline at the middle drum for the case of 12 and 18 holes were the highest.

Velocity vectors and temperature distributions on X-Y plane of rotary drum dryer simulation which varied with time in period of 200 – 1,600 seconds are shown in Figure 9. At 200 seconds (Figure 9(a)), the temperature was increased on time started from the edge of the drum, and the velocity vectors discharged from the ventilation holes to surrounding due to expansion effect from the increasing air temperature. When time became 400 seconds (Figure 9(b)), the air temperature near the drum edges was higher and the velocity vectors discharging from the holes were also larger. At 600 seconds (Figure 9(c)), the area of air temperature near the drum edge became larger than those former cases, but the air temperature inside the drum still lower and comparable to those former cases.

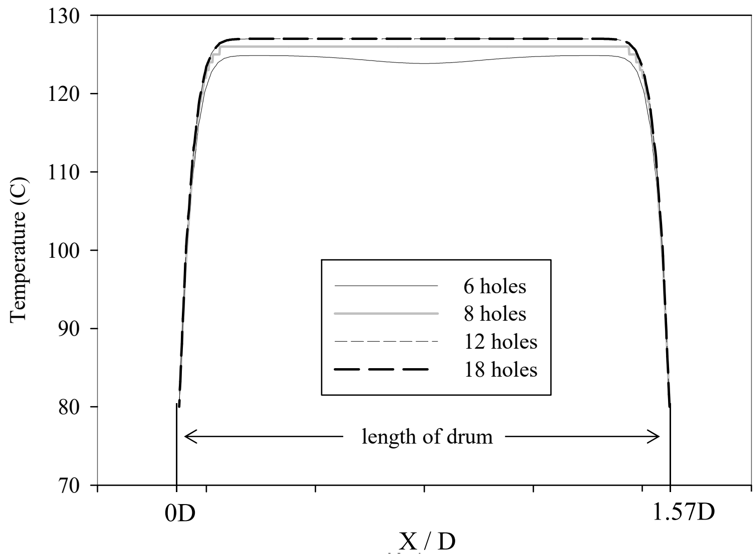
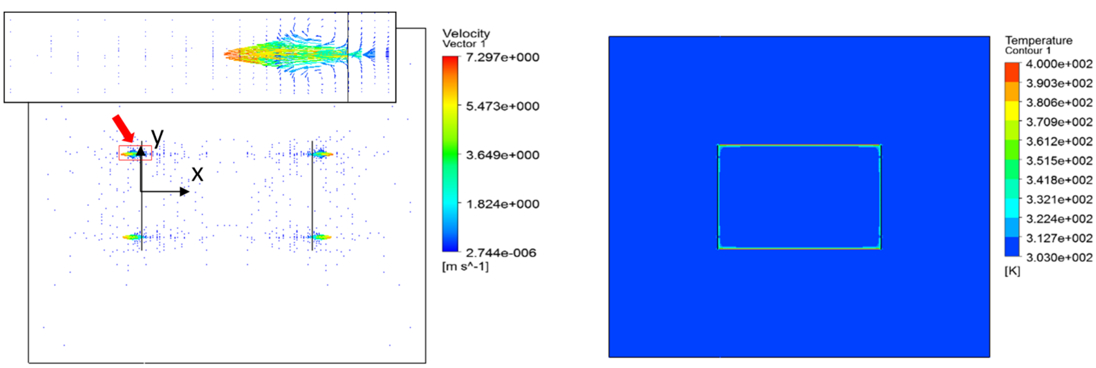
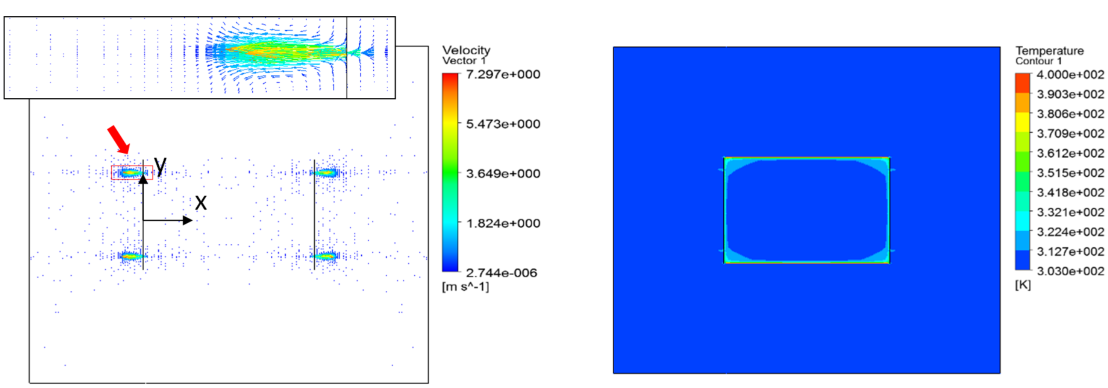


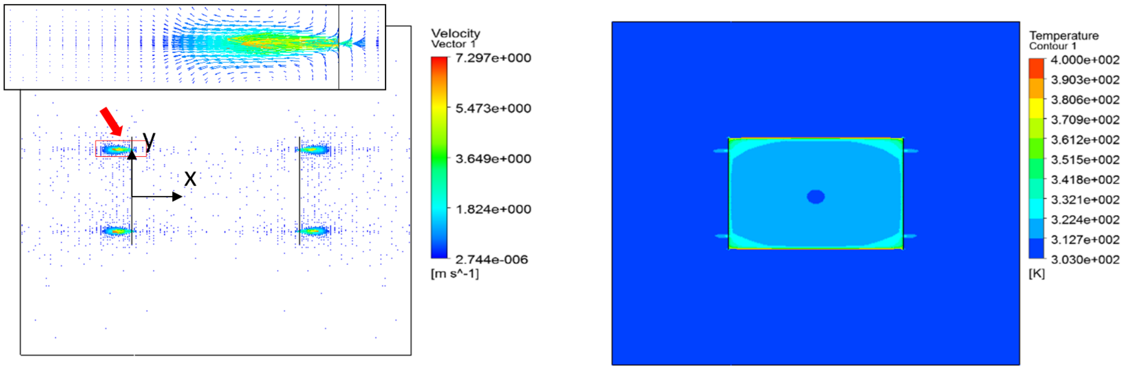

**Fig. 8.** Temperature along the centreline at the middle drum



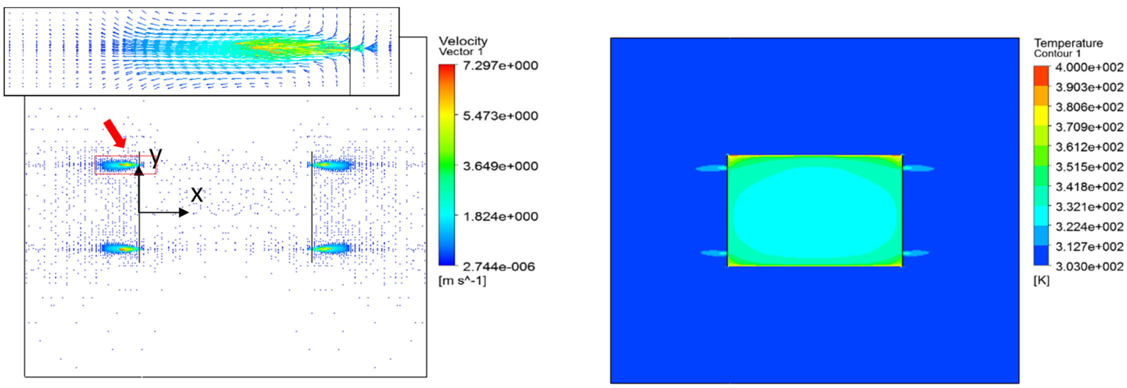

(a) At 200 seconds



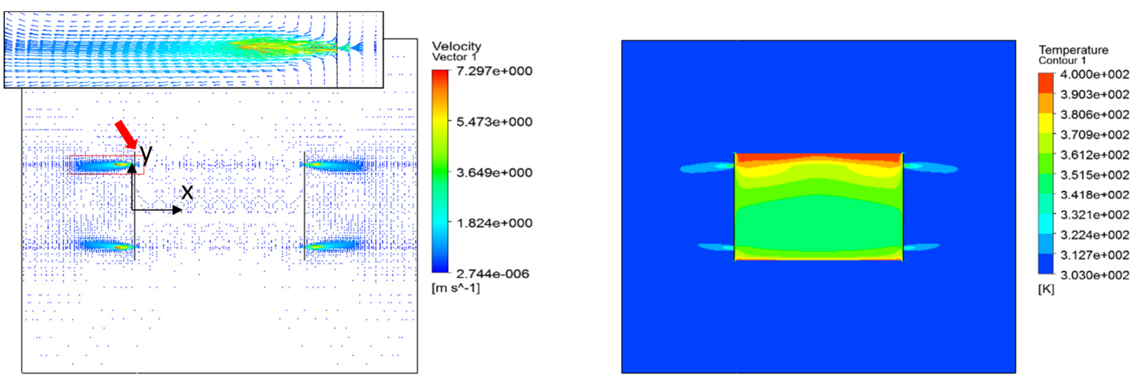

(b) At 400 seconds



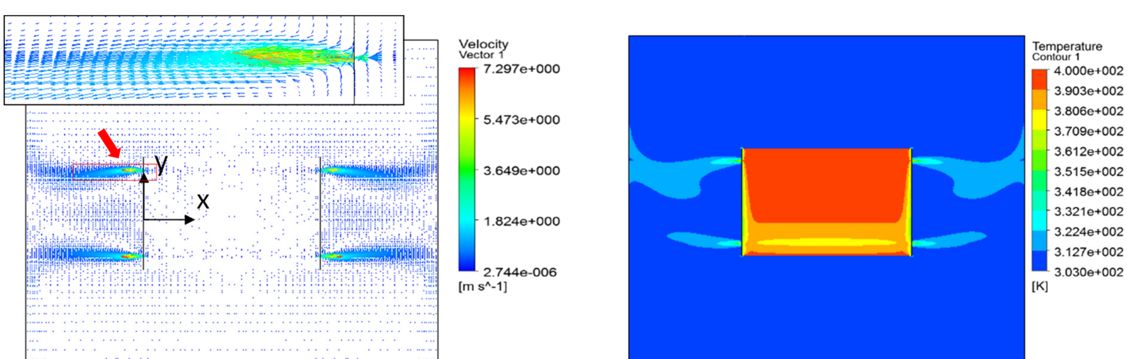

(c) At 600 seconds



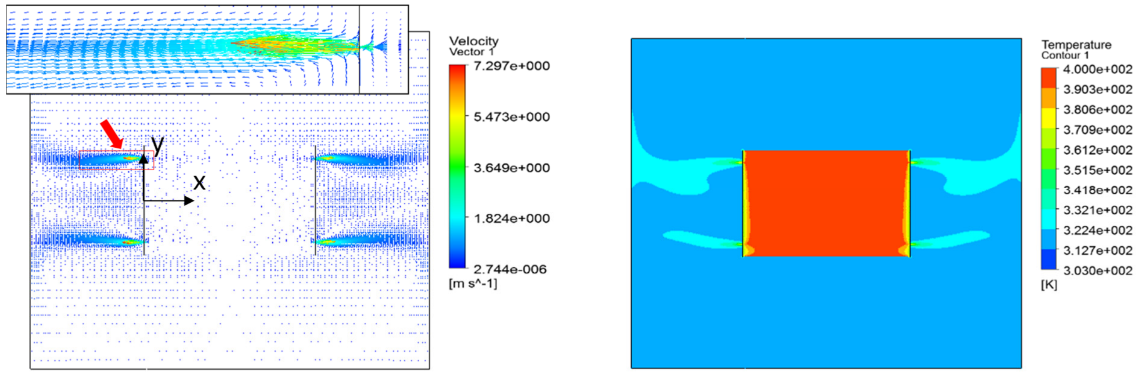

(d) At 800 seconds



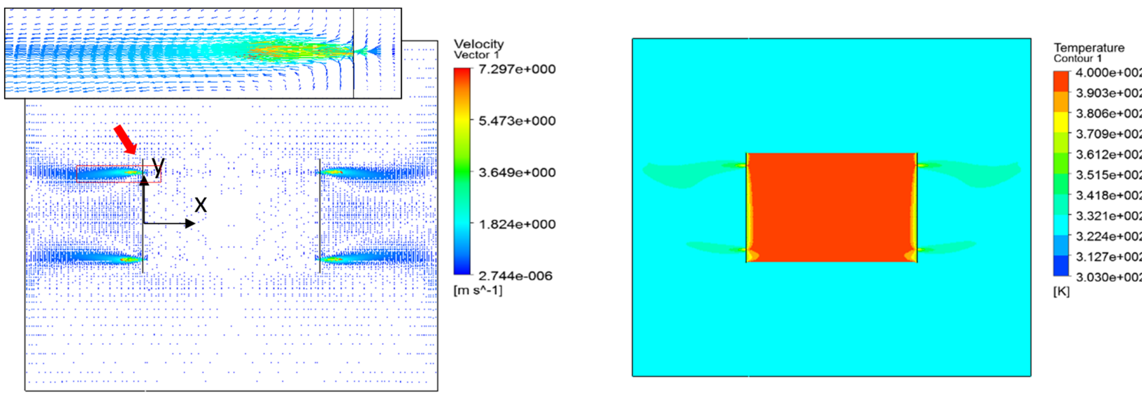

(e) At 1000 seconds




(f) At 1200 seconds




(g) At 1400 seconds




(h) At 1600 seconds

**Fig. 9.** The simulation results on X-Y plane, Left: Velocity vectors, and Right: Temperature distributions (continued)

At 1,000 seconds (Figure 9(e)), asymmetry temperature distributions were appeared due to the effect of natural heat convection [28]. The high temperature was found in upper section of the drum, and then the lower temperature was found in below section of the drum. The different temperature along the height of the drum was directly influenced to the air expansion of the drum which can be identified from discharging air velocity at upper ventilation hole was higher than that of lower ventilation hole (Figure 9(e), left). Afterwards, at 1,200 seconds (Figure 9(f)), the area of high temperature distribution inside the drum became larger, but the asymmetry temperature distributions were found. For 1,400 seconds (Figure 9(g)), and 1,600 seconds (Figure 9(h)), showed the uniform temperature distributions for the whole inside the drum. On the average, for both 1,400 and 1,600 seconds were shown to have the highest velocity flow discharging from ventilation holes.

## 4. Conclusions

In this work, a rotary drum dryer was designed and fabricated by varying ventilation hole numbers at 6, 8, 12, and 18 holes which was drilled on the drum caps. In order to observe hot air velocity discharging from the ventilation holes and air temperature distributions inside the drum, CFD technique was adopted under transient simulation. The temperature distributions on the drum surface and the drum caps of the experimental apparatus which were captured using infrared thermal imager were specified in the boundary conditions of numerical domain. The results showed that the air temperature inside the drum increased depending on the time. Hot air inside the drum discharged to surrounding due to expansion effect from the increasing of air temperature. The air temperature at the drum center in condition of ≥12 holes was the highest with the shortest time. At 1,400 and 1,600 seconds for the case of 12 ventilation holes, temperature distributions were more uniform that the former times. These results suggested that velocity flow and temperature distributions of different ventilation holes and temperature variations have to be studied further.

**Acknowledgement**
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# APPENDIX 2

Effects of temperature variation through drying bed on appearance of dried palm fruit in a lab-scale batch dryer

(This manuscript is being drafted)

# Effects of temperature variation through drying bed on appearance of dried palm fruit in a lab-scale batch dryer

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ABSTRACT

Effects of temperature variation of dried palm fruit were studied in a lab-scale batch dryer. In the experiment, dryer was simulated with same to conventional batch dryer in industry. Temperature of hot air was controlled at 110$^{o}$C and the hot air passed through the palm layer in the chamber. Thermocouple was replaced in every layer of drying palm to monitor the temperature inside chamber. The results showed that dried palm at the bottom layer have better quality than half height and upper layer. The temperature variations in palm fruit bed have influenced on the quality of final product. In this study was found that there is an effect of bottom and upper layer position to the final dried palm. During drying, the palm kernel appearances were also visualized by randomized half-cutting. This research reveals the appearance of oil palm kernel depended on temperature variation in drying process that heat pass through from bottom to the upper part of drying chamber.

*Keywords:* Oil palm drying, Defoliate oil palm, Conventional batch dryer, Oil palm milling.

## 1. Introduction

Oil palm or scientific name as *Elaeis guineensis* is an important industrial plant for producing cooking oil, industrial oil and biodiesel as fuel. Mostly, oil palm is the main source of vegetable oil beside another vegetable oil as coconut oil in many countries. Currently, some studies have been reported on oil palm research as an edible vegetable oil (Azmi et al., 2015; Gadkari and Balaraman, 2015; Kanagaratnam et al., 2013; Lee et al., 2018; Mustapa et al., 2009; Pootao and Kanjanapongkul, 2016; Silva et al., 2013; Vincent et al., 2014; Zaidul et al., 2007a; Zaidul et al., 2007b, c). Thus, oil palm also useful as a fuel or biodiesel (Abdullah, 2017; El-Araby et al., 2017; Kareem et al., 2016; Li et al., 2018; Nongbe et al., 2017; Yasin et al., 2017). Presently, the world demand for oil palm shows a tendency to increase inline with the growing world population and therefore increase consumption of products with oil palm raw materials such as food products and cosmetics.

World oil palm production showed four leader countries, namely Indonesia (51%), Malaysia (37%), Thailand (3%) and Nigeria (2%), respectively (Varkkey, 2012). In the plantation, oil palm crops require good or suitable environmental conditions, in order to be able to produce good quality palm fruits. Overall, there seems to be some evidence to indicate that oil palm can grow well in the tropical area (Barcelos et al., 2015; Sheil et al., 2009; Verheye, 2010). There are three types of oil palm fruits; they are Dura, Pisifera and Tenera. The characteristic of Dura has thick shell, Pisifera has small kernel, and Tenera was produced by mixing of Dura and Pisifera (Babu et al., 2017; Junaidah et al., 2011; Nwankwojike, 2012).

In Thailand, there are two types of milling industry processes, namely oil palm fruit bunch (large factory) and defoliate palm fruit (small factory). The process of fresh fruit bunch (FFB) in sterilization process use steam to deactivate biological factors that could influence crude oil palm (CPO) quality (Ebongue et al., 2006; Let, 1995; Sivasothy et al., 2001), which is not exceed 5 % for free fatty acid (FFA) content in CPO product. FFB have to pre-treat before undergoing further process to inactivate high amount of lipase enzyme throughout sterilization process (Olie and Tjeng, 1974; Sambanthamurthi et al., 1991; Subramaniam et al., 2010). In general, the pressure of sterilization process was 40 psi (140$^{o}$C) for 75 minutes until 90 minutes (Chow and Ma, 2001). Furthermore, sterilization consume large amount of water usage during processing (Umudee et al., 2013; Yunus et al., 2016). Thus, high cost of wastewater treatment of that process needed as a consideration to environmental impact.

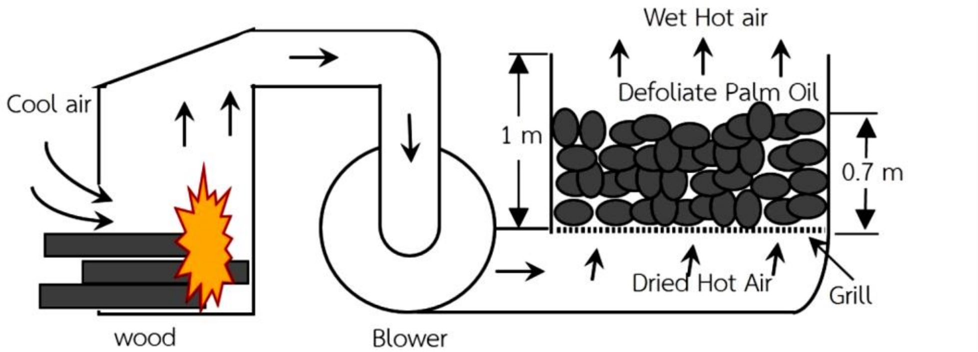



**Fig. 1.** Schematic of industrial batch drier**.**


**Fig. 2.** The photos of industrial batch drier (a) the top of batch chamber and (b) hot air supplier.

Defoliate oil palm fruit processed in small factory which covers conventional batch drying process (Fig. 1 and Fig. 2). Hot air drying is come from wood as a source of energy to grill the oil palm fruit at 110 — 120$^{o}$C. Nearby the wood kiln was located also blower to flow hot air to batch chamber which was 1.0 m in total height and 0.7 m in height for oil palm fruit to avoid over-loading and flip up the oil palm fruit.

Producing palm oil requires several processes. In general, palm oil production processes are beginning by harvesting fresh palm fruit, separation of waste and oil palm fruit, drying of palm fruit, extraction process, rough filtration, and fine filtration, as shown in Fig. 3.

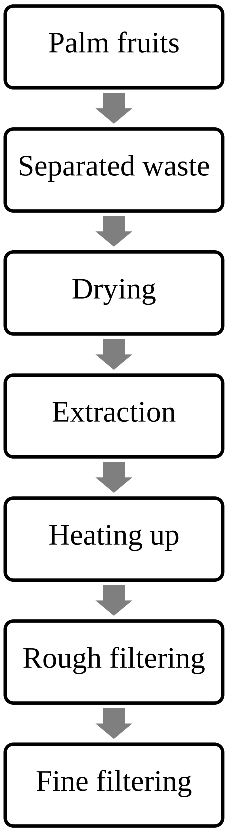



**Fig**. **3.** Diagram of oil palm processing in factory. *Source:* Babatunde et al. (1988); Vincent et al. (2014); Yunus et al. (2016).

This series of oil palm process requires precision and also carefulness to get the best quality. The quality of palm oil was based on each step in proper management. Oil palm fruit quality will be evaluated based on free fatty acid (FFA), moisture content, deterioration of bleachability index (DOBI), etc (Albert and Astride, 2013; Godswill et al., 2017; Okonkwo et al., 2012; Tagoe et al., 2012). This happened due to mass removal and moisture loss (Agarry and Aworanti, 2012; Izli et al., 2017; Reeb et al., 1999). Some agricultural products need to remove moisture to preserve their product to have prolong shelf life (Agarry and Aworanti, 2012; Izli et al., 2017). Previous studied have reported by Umudee et al. (2013) that defoliate palm fruit could be stored for about 7 days by using microwave pre-treatment with acceptable condition. Similarly with Han et al. (2012) investigated that dry heating pre-treatment could keep quality of defoliate oil palm fruit with standard value of free fatty acid (FFA), moisture content and deterioration of bleachability index (DOBI).

According to small milling factory of defoliate palm fruit, energy consumption in drying process is the highest energy usage compare to other processes. During period of drying process, it takes up to 30 — 40 hours depending on palm fruit conditions. Ripe palm fruit need less energy rather than unripe palm fruit; it is due to overripe palm fruit being softer than unripe palm fruit. The temperature of hot air during drying process has to maintain at 110 — 120$^{o}$C. After drying process, there is a criteria to evaluate cooked palm fruit by visual appearance of palm kernel which is changed from white color to colorless as shown in Fig. 4. Fig. 4 is comparison of fresh palm fruit (white color of kernel and orange color of mesocarp), nevertheless for cooked palm fruit (colorless of kernel and brownish color of mesocarp). Meanwhile, it is ready for further oil extraction process. In spite of that, palm fruit without drying produce less oil.

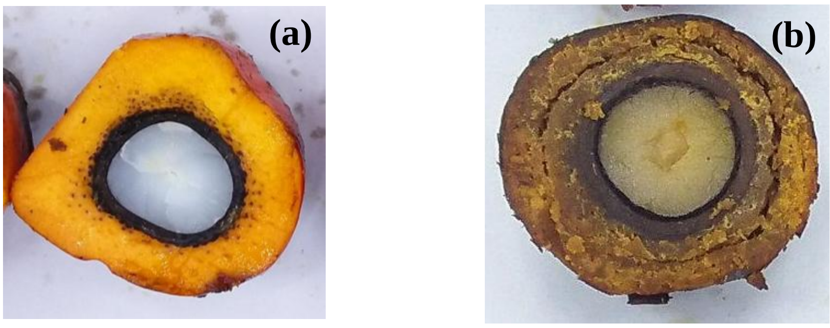



**Fig. 4.** Visual appearance of oil palm fruits in different conditions of (a) fresh oil palm fruit and (b) cooked oil palm fruit.

Conventional batch drying process for defoliate oil palm was applied broadly in southern of Thailand. A major problem of this conventional drying process has to flip up and down palm fruit to overcome overcooked. This process still conducts wood as a fuel. This indicates a need to understand the effect of temperature in conventional batch dryer by performing in a laboratory dryer. There was no research report found on temperature effect in oil palm batch drying process. The major objective of this study was to investigate the effect of temperature variation in oil palm bed during drying process in conventional batch dryer. The characteristics of internal palm fruits during drying were also visualized.

## 2. Material and methods

### 2.1 Defoliate oil palm fruit collection

Fresh defoliate oil palm fruits were collected from an oil palm milling factory in Hatyai, Songkla province, Thailand. In this study, the average weight of a defoliate oil palm was 14 ± 2 gram with average diameter of 2 ± 0.5 cm, and the color was in orange. Before undergoing of drying process, the defoliate oil palm fruit have to sort out from waste by using rotary separator. Then, 113.8 kg of defoliate oil palm fruit were put into the dryer and heated at a constant temperature of 110$^{o}$C. This condition is according to industrial practice in Thailand.

## 2.2 A lab-scale batch dryer

In order to control the drying conditions being the same to industrial dryer conditions, the laboratory batch dryer were designed as shown in Fig. 5. The lab-scale conventional batch drying system consisted of drying chamber, heating chamber, blower, speed controller (inverter), flow measurement device (orifice plate and u-tube manometer) as shown in Fig 6.-Fresh air at room temperature was induced by blower and heated up by heater chamber at 110$^{o}$C. For industrial practice, the temperature was fluctuated depend on wood consumption during drying. The velocity of hot air is 1 m/s and it was constantly blowing from inlet air throughout the whole chamber. For the hot air was set 110$^{o}$C to dry the palm oil. The drying chamber was made from steel sheet that was insulated by fiber glass. The diameter and the height of dryer chamber were 50 cm and 200 cm, respectively. The temperature of oil palm bed was measured for 6 points positioned as shown in Fig. 6 using thermocouples type K and recorded by a data logger (Hioki, LR8400, Japan). The other positions of thermocouple are at the air inlet, outlet, and at the heater chamber. For weighing of drying palm fruit, the connector between heater chamber and drying chamber (Fig. 6) was unlocked. Then, the drying chamber with palm fruit was weighted.

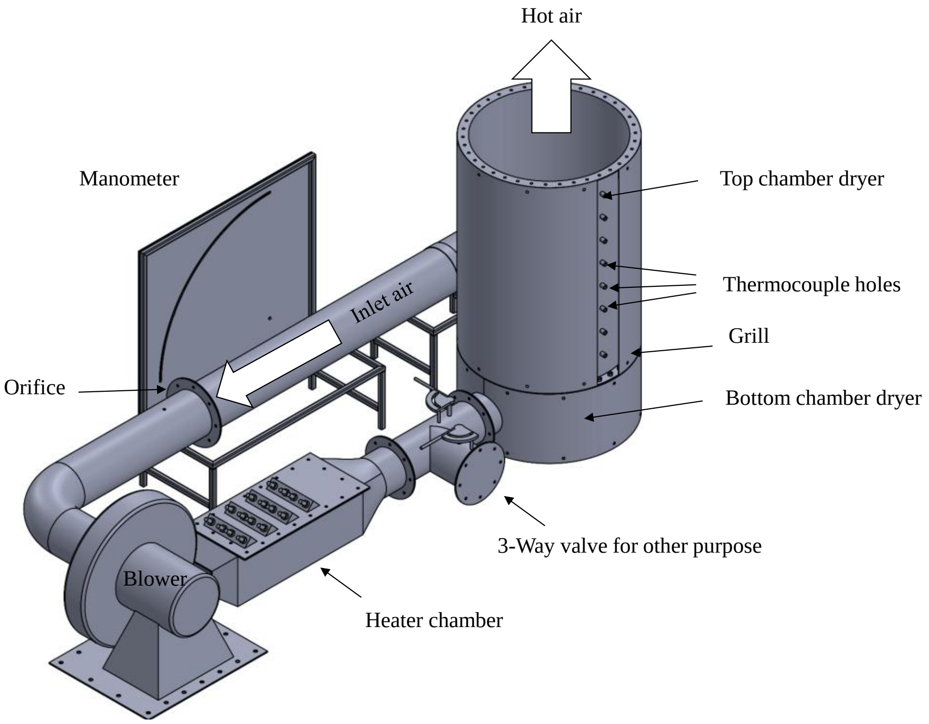



**Fig. 5.** Laboratory batch drier.

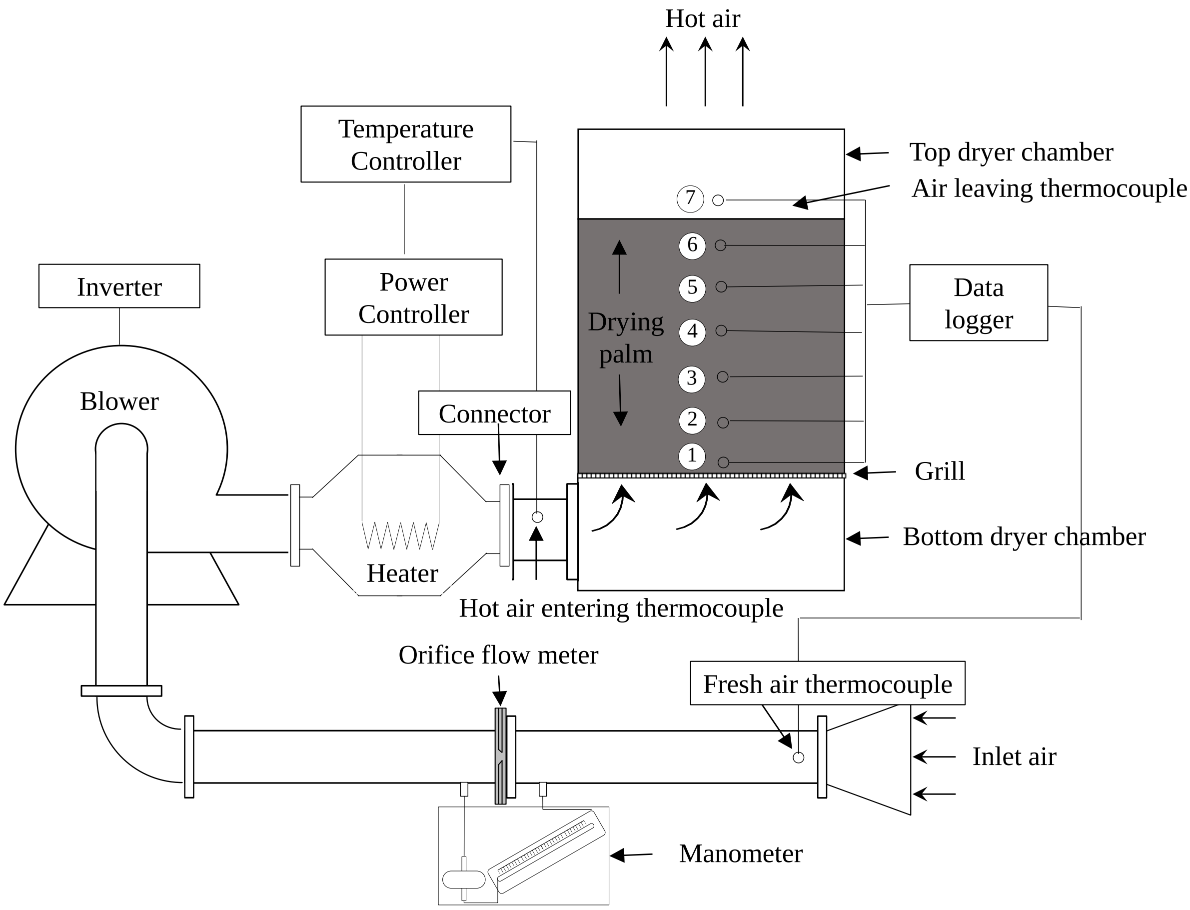



**Fig. 6.** Schematic of laboratory batch drier.

2.3 Evaluation of moisture content

A 200-gram sample of cooked defoliate oil palm fruit was placed in stainless tray and kept in an electric oven about 110$^{o}$C. The moisture content was determined using Eq. (1) (Pootao and Kanjanapongkul, 2016).

The weight of the sample at various times can be used to determine the moisture content,

$$\% \, MC(db) = \left( \frac{W - D}{D} \right) \times 100 \qquad (1)$$

where MC (db) is the dry-basis moisture content of cooked oil palm fruit (% dry-basis), W is the weight at every time weighting of dried palm fruit, D is the dry weight of dried palm fruit.

In drying experiments, the initial moisture content of the palm fruits was recorded. In order to monitor the drying process, the moisture ratios were calculated which is derived from below as Eq. (2):

$$MR = \frac{(M_t - M_{eq})}{(M_{in} - M_{eq})} \qquad (2)$$

$M_t$ is the moisture content fresh oil palm fruit at every time (% dry-basis fraction), $M_{in}$ is the initial moisture content of the fresh oil palm fruit, dry-basis fraction (% dry-basis), $M_{eq}$ is the equilibrium moisture content of dried palm fruit (% dry-basis).

The drying rate per unit of time during drying was calculated from the following Eq. (3):

$$Drying\,rate = \frac{(M_t - M_{t+\Delta t})}{\Delta t} \qquad (3)$$

where $M_t$ is oil palm moisture at time (dry-basis fraction), $M_{\Delta t}$ is moisture of oil palm, at time t + Δt (dry-basis fraction), Δt is drying time interval (min).

2.4 Appearance of cooked defoliate oil palm fruit

The appearance of cooked defoliate oil palm fruit was visually observed. For industrial observation, the cooked palm fruit was based on colorless of kernel and brownish color of mesocarp as previously shown in Fig. 4b. Usually, the drying period up to 30 — 40 hours to achieve good quality of cooked palm fruit.

For the experiment activity, dried palm fruit were periodically collected at the half height of palm bed which was cut across to examine the kernel appearance. The photographs of cut palm fruit were taken under a constant light.

## 3. Results and discussions

3.1. Oil palm temperature and moisture content during drying

Fig. 7 shows the temperature variations during drying of each point in palm fruit bed as referenced in Fig. 6. At the point 1, the temperature of palms was increased immediately from initial at room temperature in the first two hours (marked a and b) due to it was the first entering layer of the hot air. After 4 hours, palm temperature of point 1 become constant. It can be noted that the drying palms located at the bottom layer that matched with temperature at the point 1 were heated by hot air with temperature of ≈100$^o$C along 22 hours (starting at 4 hours). The effect of temperature variation will be discussed on observation of internal palm appearance in the next section.

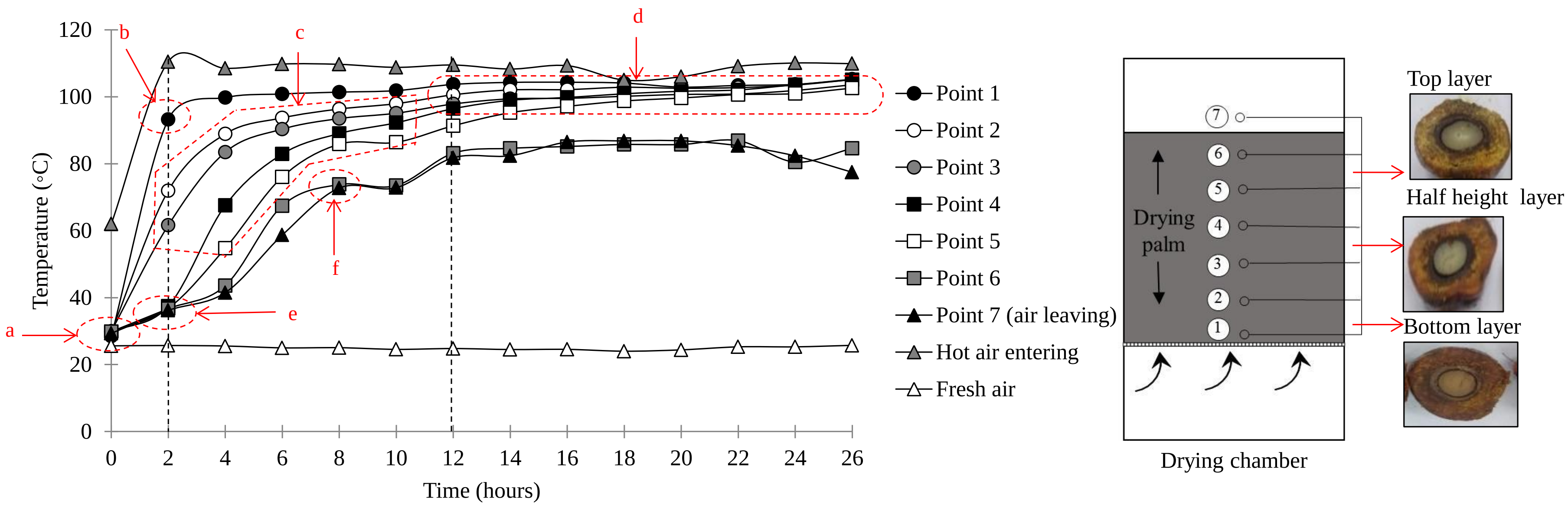
The temperatures of palm at the point 2 — 5 during 12 hours starting from beginning were varied according to drying time (marked c) while these temperatures after 12 hours were constant (marked d). This means that the palm located between points 2 and 5 were heated up by the hot air having temperature of ≈100$^o$C for 14 hours starting from 12 hours.

In the first 2 hours, the palm temperatures at the point 4 to 6 were increased gradually (marked a and e), this result may be explained by the fact that they are located near to air outlet and heat transfer from hot air is dropped before it reaches to these points. In addition, the temperature at the point 6 was the same to the temperature at the point 7 (air leaving) at 8 hours (marked f). During this, the top layer of palms became lower than the position of thermocouple at the point 6 due to the contraction of drying palms. Consequently, after 8 hours starting from beginning, the thermocouple at point 6 measured the temperature of hot air notified by the same temperature at the point 7 (marked f).

Based on Fig. 7, half-cut palm fruits namely top layer, half height layer and bottom layer at 26 hours drying period were also shown. At the bottom of drying chamber performed as point 1 and 2 were visually cooked with colorless of kernel and brownish color of mesocarp. However, in the half height and upper of batch dryer presents uncooked palm fruit with white spot at the center of kernel and yellowish color of mesocarp. It is almost certain that moisture accumulation was increased from bottom to the top layer of dried palm.

There was a significant difference between air leaving at the exit and hot air entering the drying chamber. From air leaving at the exit, it can be seen that heat conduction from the bottom of dryer chamber to the top of drying chamber was low. Thus, the designs of drying chamber have influenced on heat transfer distribution (Gnyrya et al., 2015; Kreith and Chhabra, 2017; Reymond et al., 2008). If the temperature rises more than $110^{o}C$, the oil palm quality will be low. This value agreed with previous studies reported as a standard of drying in industrial to maintain the efficient drying process (Ab Hadi et al., 2015; Junaidah et al., 2015; Sarah and Taib, 2013). It is necessary to maintain temperature $\pm$ $110^{o}C$, due to overcome overcooked at the bottom layer. For temperature more than $110^{o}C$, the condition of bottom layer part was overcooked, whereas the upper part was in a good quality.

As Fig. 8a shows, the decrease trend of oil palm moisture ratio for 26 hours drying period. Moisture ratio decrease immediately from beginning and after 12 hours of drying time, it was decrease gradually. Fig. 8b shows the drying rate of oil palm during 26 hours of drying period. It is apparent that drying rate of oil palm was increased suddenly at start of drying and then immediately decrease at 4 — 12 hours, and gradually decreases in 12 — 26 hours that nearly a constant rate. These results indicate that it was due to high moisture content in the early stage of drying process, followed by low moisture content.




253
254 **Fig. 7.** Temperature changes of batch dryer (dried palm appearance from every layer at 26 hours drying period).

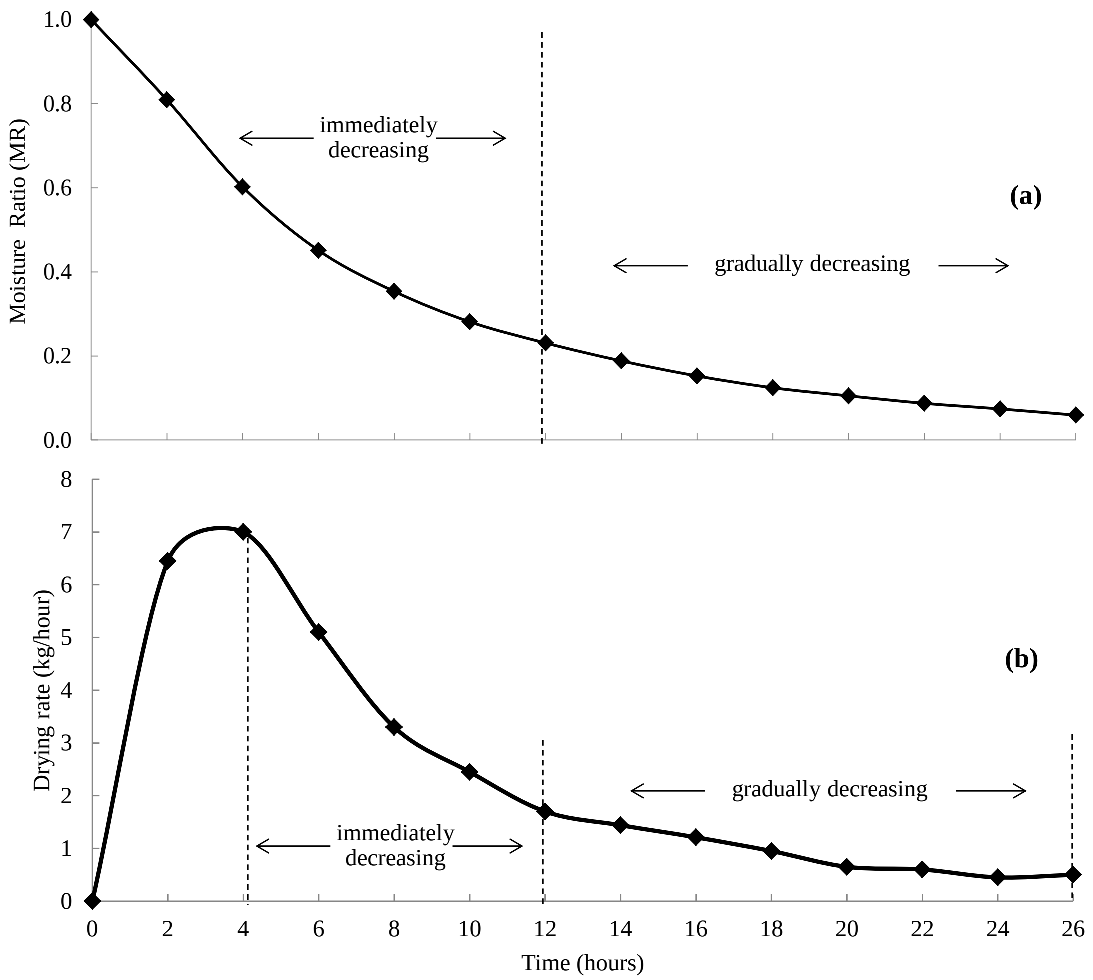



**Fig. 8.** (a) Moisture ratio of drying process (b) drying rate of oil palm batch drying process.

3.2. Visual appearance of oil palm fruit

The appearance of dried palm fruit at half of palm layer in drying chamber at 8 — 26 hours of drying period was shown in Fig. 9. The longer drying period was shown the browning color of dried palm. Fig. 9a and 9b represented uncooked palm fruit with white color of kernel and yellowish of mesocarp. Whereas, Fig. 9c — Fig. 9f show white spot in the centre of kernel and yellowish of mesocarp. This study found that 26 hours drying period of oil palm cooked since the kernel is colorless and mesocarp is browning as shown in Fig. 9g. Small palm kernels are more colorless than large kernels, thus heat transfer from hot air into the center is faster.

Fig. 10 shows dried palm fruit after 26 hours drying period taking at the center of drying chamber in different palm layers, namely upper, half height, and bottom of batch dryer. It can be seen that palm fruit at the bottom of drying chamber is mostly colorless of kernel and brownish of mesocarp. It was also shown that cooked palm at bottom is better than that at half height and upper drying chamber. The results of this are due to (1) moisture accumulation from bottom layer to the upper layer of dried palm, (2) drying period for getting high temperature (≈100$^{o}$C).

As Fig. 10a and 10b represent quite similar visual appearance, this is match with temperature ≈100$^{o}$C during 14 hours (starting from 12 hours of drying time) with temperature between point 3 and 4 (for half height layer, point 5 and 6 for upper layer). Fig. 10c matches with temperature at point 1. It takes about ≈100$^{o}$C almost 22 hours. It looked very dry as compare to Fig. 10b, but it is not over-cooked. However, some palms of Fig. 10a and 10b have white color at the center of kernel. The main finding for this research, there is an effect layer of bottom and upper to final product of dried palm. In the factory, there is only 20 % of overall dried palm that could flip over. So that, factory needs to take this possibly consideration. Those variation of color at different positions showed that there is a need to flip up and down oil palm fruit during drying process. Furthermore, variation of dried product quality is one of the weakness batch drying process (Alam and Sehgal, 2014; Arlabosse et al., 2005; Javanmard et al., 2009; Ndukwu, 2009).

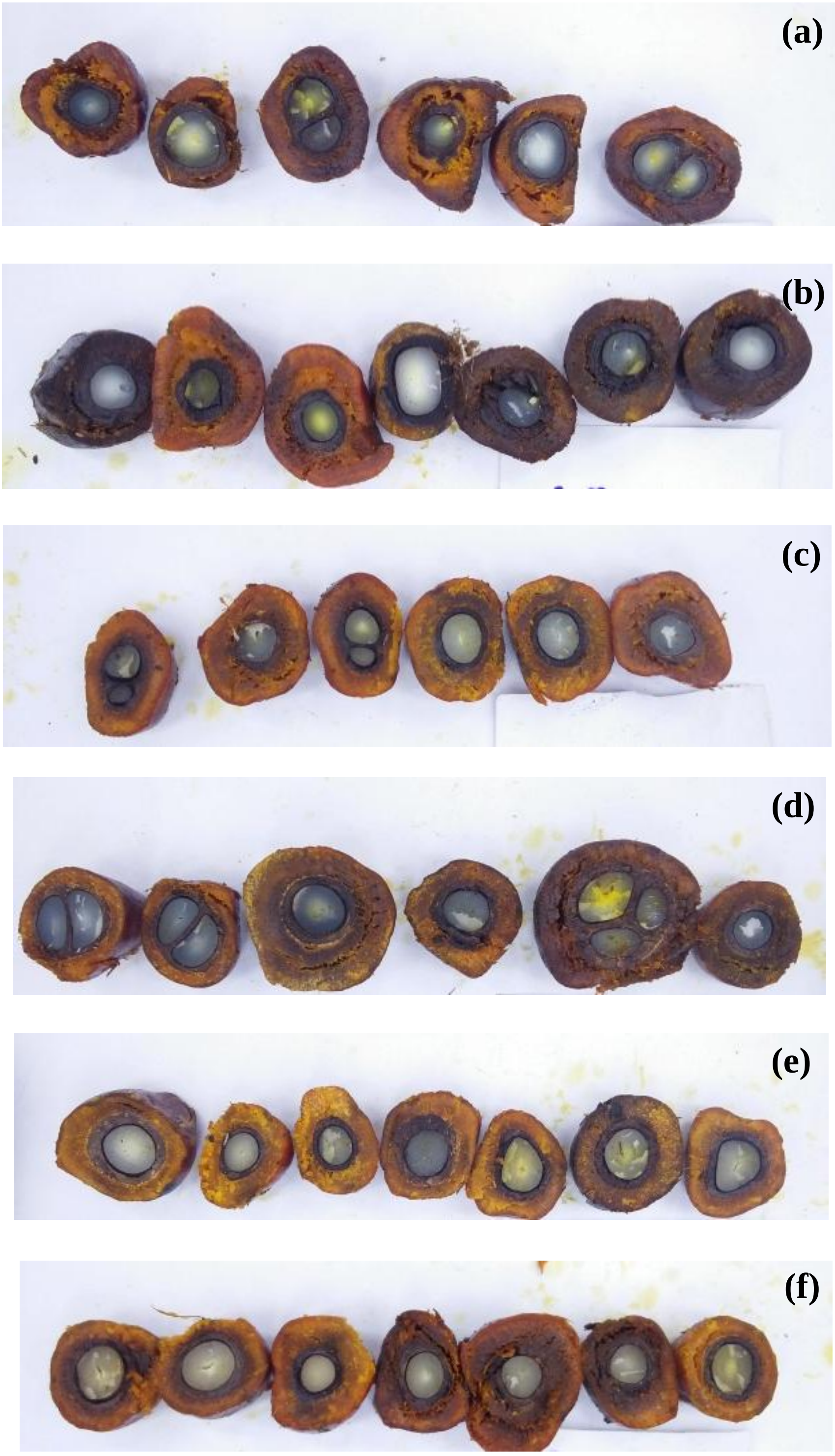



**Fig. 9.** Visual appearance of internal dried palm fruit in different drying time at (a) 8 hours (b) 14 hours (c) 18 hours (d) 20 hours (e) 22 hours (f) 24 hours and (g) 26 hours.


**Fig. 9.** Visual appearance of internal dried palm fruit in different drying time at (a) 8 hours (b) 14 hours (c) 18 hours (d) 20 hours (e) 22 hours (f) 24 hours and (g) 26 hours (continued).


**Fig. 10.** Visual appearance of internal dried palm fruit in different position of (a) upper of batch dryer (b) half height of batch dryer and (c) bottom of batch drier.

## 4. Conclusion

As a conclusion, pilot conventional batch drying process showed the effects of variation temperature on drying palm during the process. The temperature variation could influence the final product of oil palm fruit. The findings of this study suggest that small kernel is better to located in the top drier chamber. In general, batch drying is giving shorter time drying period than industrial practise, because heat chamber can control temperature during drying period constantly. The appearance of oil palm kernel depended on temperature variation in drying process that heat pass through from bottom to the upper part of drying chamber. In this study was found that there is an effect of bottom an upper layer position to final dried palm. Moreover, additional worker must flip over to maintain quality of cooked oil palm. This research will help in future development of oil palm drying process to develop new method that is suitable applied for small factory. A further study focusing on flipping machine is therefore suggested for oil palm drying.

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# APPENDIX 3

Development of rotary drum dryer for defoliate oil palm sterilization

(This manuscript is being drafted)

# Development of Rotary Drum Dryer for Defoliate Oil Palm Sterilization

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ABSTRACT

Rotary drum dryer were designed for palm fruit sterilization in this research. In the experimental design, the drum has 57.5 cm in diameter and 90 cm in length. The buttom of the drum was placed of burner to heating up the drum. It was rotated by controlled using inverter with low rotating speed of 1.68, 4.14, and 8.34 rev/hour. To keep temperature 120$^{o}$C, the ventilation hole was designed with variation of 9, 18, and 36 holes, respectively. The results showed that there is small effect of rotation speeds and ventilation holes in every case study. Rotation speed of 1.68 rev/hour with 36 ventilation holes and rotation speed of 8.34 rev/hour with 36 ventilation holes were the lowest fuel consumption of 0.49 kg per hour. After 12 hour of drying period observed to be constant moisture content and stable condition in this research.

*Keywords:* Oil palm drying, Palm sterilization, Rotary drum dryer.

## 1. Introduction

Oil palm is an important crop that is beneficial for human consumption as vegetable oil. It is commonly used as basic material for some products namely margarine, cookies, chocolate, ice cream, bakery product and also non-edible food such as soap, candle, and other cosmetic items (Azmi et al., 2015; Rios, Pessanha, Almeida, Viana, & Lannes, 2014). Those the advantages of oil palm adversely affect to human such as because of stability shelf life, the taste of consuming the product and good texture characteristics (Da Silva, Domingues, Chiu, & Goncalves, 2017). Oil palm has been easy to utilized as daily needed and it also has competitive price comparing to others vegetable oil (Salas, Bootello, Martínez-Force, & Garcés, 2009).

Oil palm plays important role as major oil consuming in the world as 33.6% (MPOC & APOC, 2010). Thus, Malaysia, Indonesia and Thailand are the top three leader countries for oil palm production (FAO, 2013). Oil palm can grow well in tropical area with rainfall of 2000 — 2500 m per year (Henson, Noor, Harun, Yahya, & Mustakim, 2005; Kallararacleal, Jeyakumar, & George, 2004). Oil palm could get high productivity by applying good technical management, which is fertilization (Goh, Teo, Chew, & Chiuw, 1998). There are some criteria to increase productivity of oil palm, they are selection of land, planting material, technical harvesting and good environmental condition (Salas et al., 2009).

In Thailand, oil palm factory was divided into two types, namely big factory for palm fruit bunch and small factory for defoliate palm fruit. Fresh palm fruit have to pursue sterilization process as function to inactivate enzyme that could affect biological factors and then deterioration of oil palm fruit (Hamzah, 2008; Pootao & Kanjanapongkul, 2016; Vincent, Shamsudin, & Baharuddin, 2014). As the early stage of palm fruit process, sterilization is such a critical operation process that ensures the successfulness for the next step of processes. Sterilization process give great recovery and quantity of oil palm fruit which is extracted from mesocarp of palm fruit (Jusoh, Rashid, & Omar, 2013). Sterilization process is making use of steam with high pressure 15 — 45 psi about 90 minutes (Chow & Ma, 2001; Sivasolhy, 2000). After sterilization process, palm fruit could be proceed to extraction process, heating up, rough filtration, and fine filtration (Yunus, Zurina, Syafiie, Ramanaidu, & Rashid, 2016).

Defoliate palm fruit is processed in small factory of conventional batch drying process. In the drying process, the fuel used is wood and the usage of blower as function passing the hot air to batch chamber. The height of batch chamber is 1 meter, contained of 0.7 m height of defoliate palm fruit. Temperature inside the chamber is about 110 — 120$^{o}$C to ovoid overcooked or not cooked palm fruit. In this conventional drying method, it takes about 30 until 40 hours of drying period to get wanted dried palm fruit.

Conventional batch drying is widely used in Southern of Thailand. A major problem faced is palm fruit need to be flipped over to overcome the overcooked. Huge number of labor need to be consider for future concern. Heat loss during drying also needs a consideration, since the batch chamber does not have cover. Newly design of rotary drum dryer is needed to be evaluated to understand possibility application near future.

Some papers were trying to develop and check the performance of the newly design dryer for agricultural product. Tarhan, Yildirim, Tuncay, and Telci (2008) investigated about batch rotary dryer for dry medicinal and aromatic plants. For batch system in the research, the rotary drum dryer were designed with perforated drum 2 mm in diameter (Fig. 1). For the dry hot air was passed through the perforated drum. And then it showed good result in 26 % reduce drying time and reduce specific energy consumption.

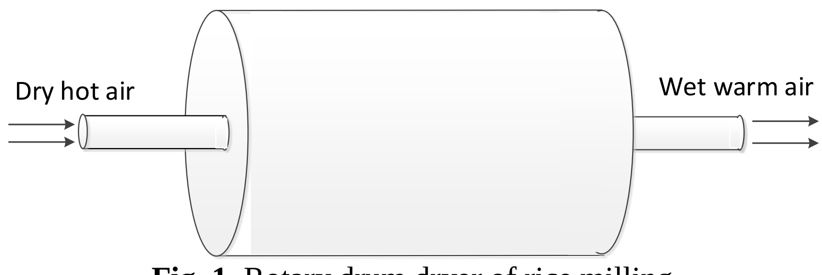


**Fig. 1.** Rotary drum dryer of rice milling

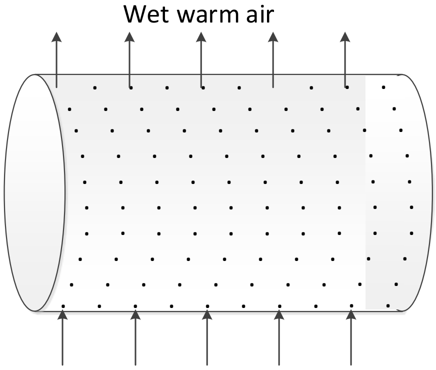


**Fig. 2.** Rotary drum dryer of pepper mint

In another agricultural product which is medicinal and aromatic plant was also being developed. Firouzi, Alizadeh, and Haghtalab (2017) found that a new design of rotary dryer to get high quality and minimum energy cost during operation. The rotary drum was designed with hot air come through the inlet pipe and outlet pipe for wet warm air flow as described in Fig. 2.

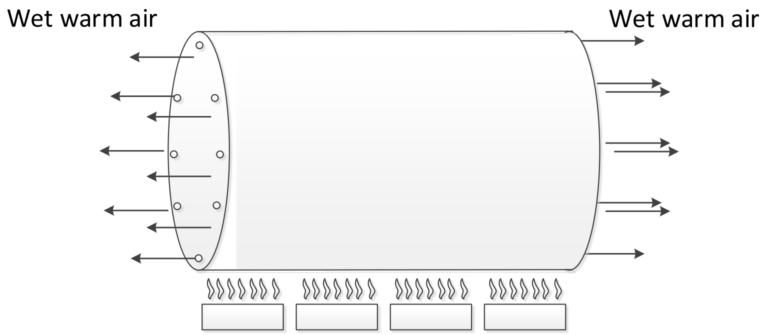


**Fig. 3.** Newly-designed of rotary drum dryer

While some research has the mechanism by which rotary drum dryer build up with ventilation holes has not been established. In Fig. 3, the wet warm air will pass through the ventilation hole. It was designed with burner at the bottom of the drum. In this study, the batch rotary drum dryer was developed for palm fruit that was heated by direct burning from flame. It has advantage that biomass can be used as fuel. In this study the ventilation hole would be examined by using CFD.

## 2. Materials and methods

### 2.1 Defoliate palm fruit

Mature palm fruit were collected from an oil palm company in Hatyai, Songkla province, Thailand. The average individual weight palm fruit were 14 ± 2 gram with average diameter of 2 ± 0.5 cm. To control variation of maturation, the color of mature palm fruit is fixed with orange color. Defoliate palm fruit were shown in Fig., and cut palm fruits were shown in Fig., respectively.

## 2.2 Experimental design

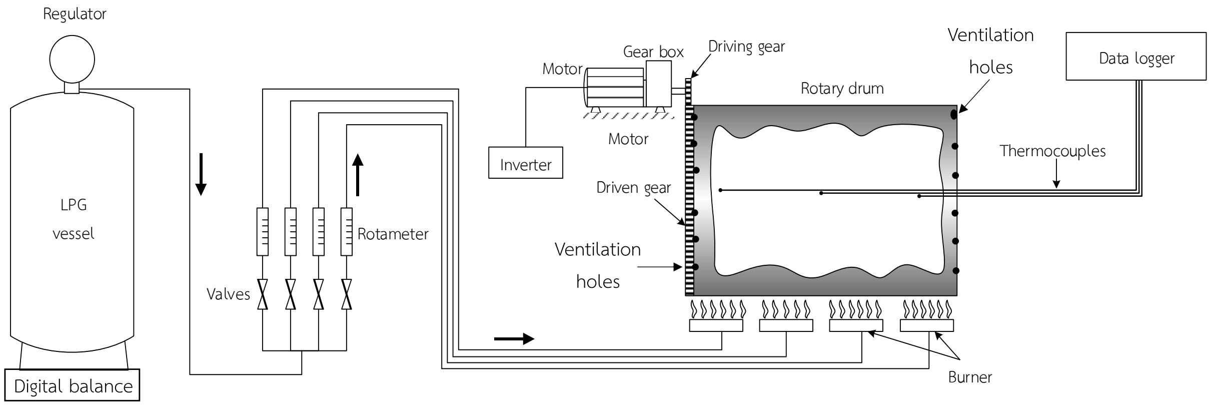


**Fig. 4.** Rotary drum experimental setup

A new design of rotary drum dryer in the experiment was shown in Fig. 4. The drum was built with steel sheet rolling on cylindrical shape. The diameter and length of rotary drum were 57.5 cm and 90 cm, respectively. Inside the rotary drum consist of cage to avoid direct burning to palm fruit. Rotary drum dryer was supported by 4 bears which were rolling at fix position during experimental activities (Fig. 5). At the bottom of drum were placed 4 stoves for direct burning of LPG. On the top side of the drum was also supported by roller to control drum rotation. On the other side was arranged by motor gear. The rotation was adjusted by using inverter. The drum was rotate slowly to prevent bruise from contusion that could affect enhancement of FFA percentage.

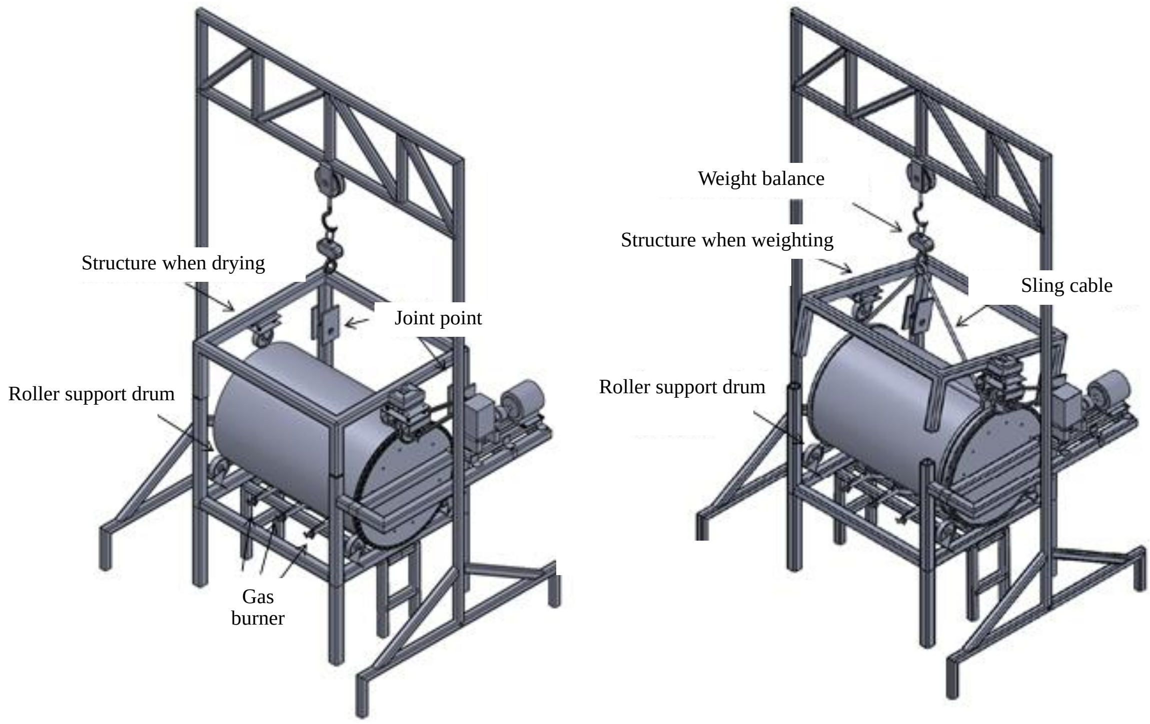


**Fig. 5.** Rotary drum set up during drying

Nearby, rotameter was also installed to count flow rates of LPG and also to control temperature in the drum during drying. Every gas was monitor until the temperature stable in 120$^{o}$C. And then, thermocouple was placed inside the drum and the signal was transferred to the electronic device of data logger series Hioki, LR8400, Japan. For this research, comparable with conventional batch drying product was conducted. The mechanism drying process as shown in Fig. 6.

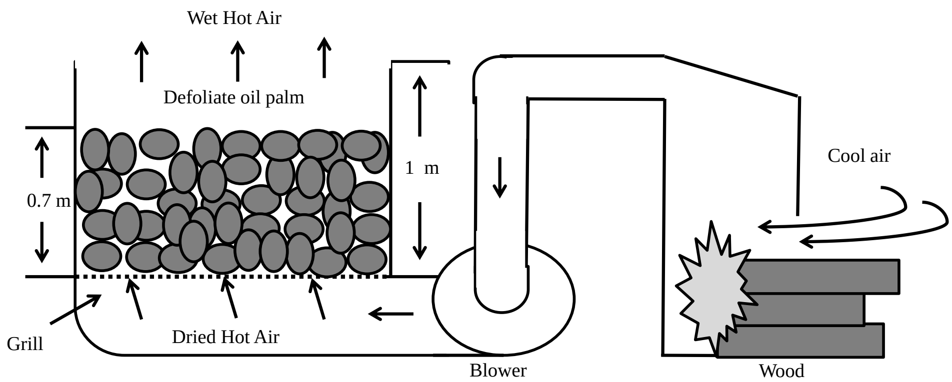


**Fig. 6.** Conventional batch dryer

2.3 Experimental methods

50 kg of palm fruit was placed into the drum manually for every batch. The cap was closed after loading. For every 200 gram palm fruit was dried in the oven to understand the dried weight of palm fruit. During drying process, drum was weighted in every 1 hour time interval to evaluate moisture content of palm fruit. The rotating speeds of this experiment were rotated slowly at 1.68 rev/hour, 4.14 rev/hour and 8.34 rev/hour.

2.4 Calculation of moisture content and moisture ratio

For calculation percentage of moisture content (kg of water / kg of dry matter) was measured by following equation:

$$\%\,MC\,(db) = \left(\frac{W - D}{D}\right) \times 100 \qquad (1)$$

Where W is palm fruit weight in every hours interval, D is dried weigh of palm fruit. In drying process, initial moisture content was compared with different conditions of experiments. This is moisture ratio which is calculated based on equation as follows:

$$MR = \frac{(M_t - M_{eq})}{(M_{in} - M_{eq})} \qquad (2)$$

Where $M_t$ is Moisture Content at drying time, $M_{eq}$ is percentage of final Moisture Content of palm fruit, $M_{in}$ is an initial Moisture content of palm fruit.

# 3. Results and discussions

3.1. Moisture content of palm fruit during drying

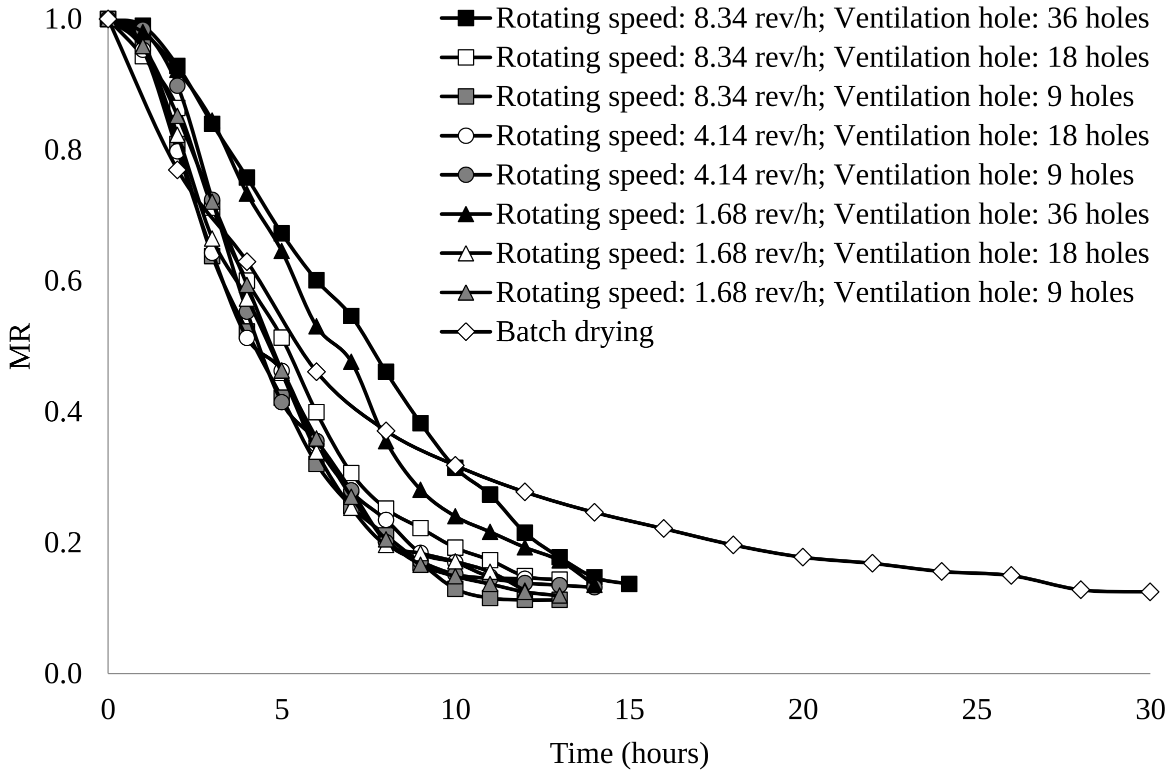


**Fig. 7.** Moisture ratio of each cases

Fig. 7. shows comparison effect of ventilation holes and rotation speed at different time. The results showed that moisture content during drying period was decreasing. There is effect of rotation speeds and ventilation holes, because of moisture content inside the drum. Rotation speed of 8.34 rev/hour with ventilation holes of 36 showed similar trend with rotation speed of 1.68 rev/hour with ventilation holes of 36, but after 5 hours temperature increase. Initial moisture content is decrease from 21.017 % to 18.206 % for rotation speed of 8.34 rev/hour with ventilation holes of 36. Whereas, moisture content also decrease from 20.296 % to 15.726 % for rotation speed of 8.34 rev/hour with ventilation holes of 36.

Moisture content of ventilation holes of 9 with rotation speed of 8.34 rev/hour and ventilation holes of 18 with rotation speed of 1.68 rev/hour also showed similar trend, but after 2 hours temperature increase. Initial moisture content decrease from 36.257 % to 27.339 % for ventilation holes of 9 with rotation speed of 8.34 rev/hour. Whereas, moisture content also decrease from 37.770 % to 30.473 % for rotation speed of 1.68 rev/ hour with ventilation holes of 18.

When drying period were more than 12 hours, moisture content of palm fruit was linear until constants condition. In addition, LPG during drying for every case was varied from 0.49 - 0.68 kg per hour. For drying, it took time for about 12 — 15 hours to change mesocarp color from orange to brownish and for kernel from white to colorless.

## 3.2. Energy consumption rate

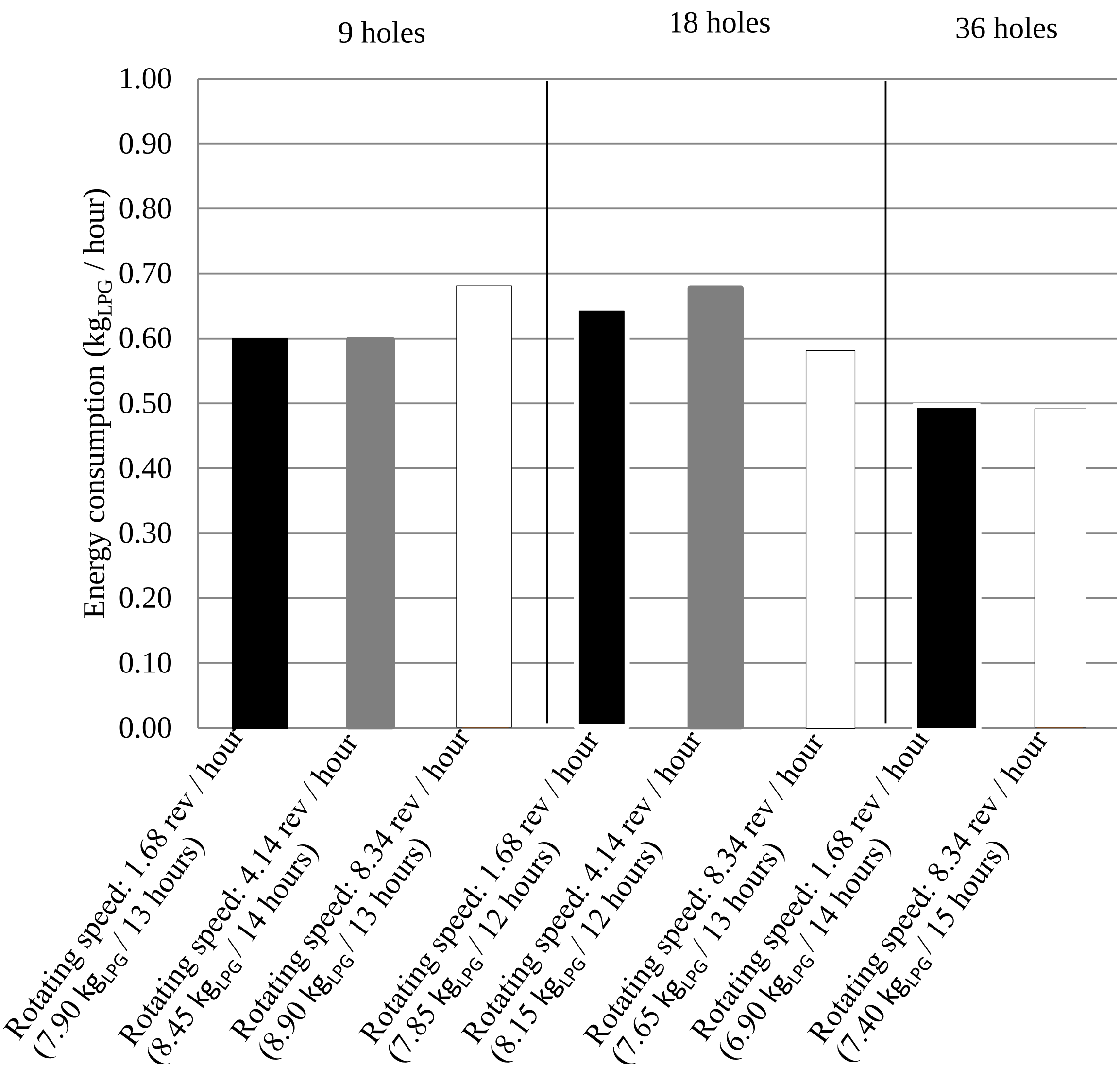


**Fig. 8.** Energy consuming rate of various drying conditions

For the energy consumption rate, rotating speed of 1.68 rev/hour and 4.14 rev/hour showed similar trend in every holes variation. Rotating speed of 1.68 rev/hour with ventilation hole of 9 showed similar trend with rotation speed of 4.14 rev/hour with ventilation hole of 9, but rotating speed of 8.34 rev/hour with ventilation hole of 9 showed the highest energy consumption as 0.68 kg per hour. Fig. 8. also shows similar trend rotation speed of 1.68 rev/hour with ventilation hole of 36 and rotation speed of 8.34 rev/hour with ventilation hole of 36, which is 0.49 kg per hour, respectively. For the highest energy consumption were 0.68 kg per hour that performed from rotation speed of 8.34 rev/hour with ventilation hole of 9 and rotation speed of 4.14 rev/hour with ventilation hole of 18.

3.3. FFA percentage and oil yield of dried palm

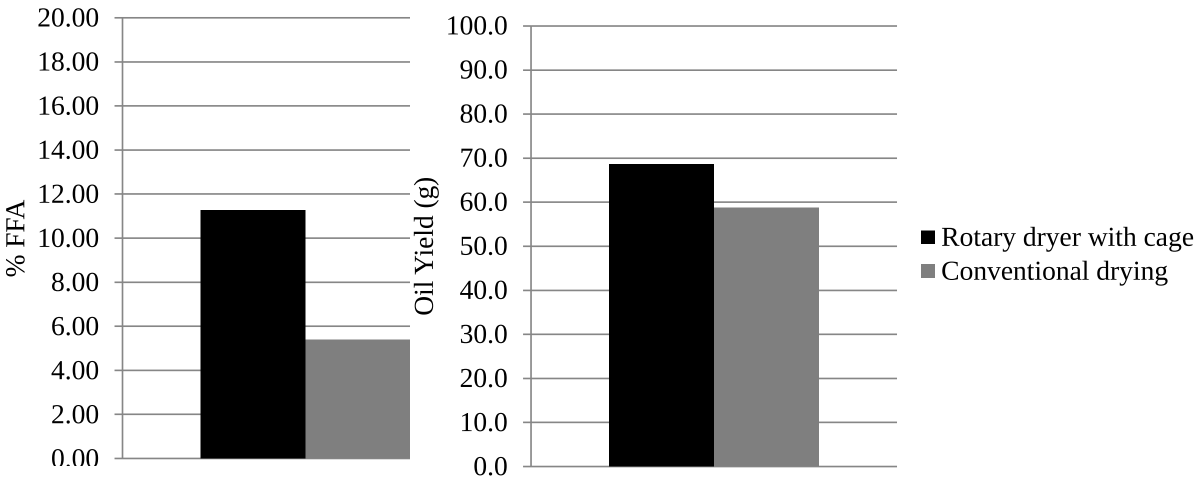


**Fig. 9.** FFA percentage and oil yield of drying palm

Fig. 9. shows FFA percentage of rotary drum dryer with cage comparing to conventional batch dryer. From this data, FFA of palm from rotary drum performs in higher value of 11.27% than FFA of palm from conventional drying with value of 5.40%. For the acceptable value percentage FFA in palm oil have to be 5%. FFA content shows the purities of palm fruit inside.

Fig. 9. also shows oil yield of rotary drum dryer with cage comparing to conventional batch dryer. Interestingly, for that data shows similar trend that oil yield of palm from rotary drum performs in higher value than oil yield of palm from conventional drying. It can be seen that rotary drum dryer performs 68.6 grams of oil yield, where as conventional dryer presents 58.7 grams of oil yield. This result suggests that rotary drum dryer give higher value of oil yield rather than conventional dryer. It might be due to homogenize-cooked palm during drying of rotary drum.

3.4. Visual appearance of dried palm

As shown in Fig. 10. the visual appearance of drying palm at rotation speed of 8.34 rev/hour with ventilation hole of 36 and rotation speed of 1.68 rev/hour with ventilation hole of 36 was performed. In Fig. 10a at 7 and 8 hours of drying period, the kernel was white color, and the mesocarp was yellow. In another hand, Fig 10a at 9 and 10 hours of drying period and also Fig. 10b at 8 hours of drying period performs results of the kernel was white spot and the mesocarp was brownish. In addition, Fig. 10b at 9 hours of drying period presents colorless of kernel and brownish of mesocarp.

7 hours 8 hours

9 hours 10 hours (a)

8 hours 9 hours (b)

**Fig. 10.** Visual appearance of drying palm at (a) ventilation holes: 36; rotation speed: 8,34 rev/hour for 7, 8, 9 and 10 hours of drying period and (b) ventilation holes: 36; rotation speed: 1,68 rev/hour for 8 and 9 hours of drying period.

## 4. Conclusion

This research is study about effect rotation speeds and ventilation holes of rotary drum dryer study on moisture content and moisture ratio of oil palm. Based on this study, rotation speeds and ventilation holes give small effect in every cases. For fuel consumption, rotation speed of 1.68 rev/hour with ventilation holes of 36 and rotation speed of 8.34 rev/hour with ventilation holes of 36 represent the lowest fuel consumption of 0.49 kg per hour. In factory, the drying process take time about 30 — 40 hours to achieved this condition. For future need to consider energy cost compared to factory.

## Acknowledgements

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**APPENDIX 4**

The effect of ventilation hole on flow behaviour and heat transfer of rotary drum dryer

(Published in *IOP Conference Series: Materials Science and Engineering 297(1),012030*)

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# A rotary drum dryer for palm sterilization: preliminary study of flow and heat transfer using CFD

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# A rotary drum dryer for palm sterilization: preliminary study of flow and heat transfer using CFD

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**Abstract**. Preliminary study in this article, the flow and the heat transfer of rotary drum dryer were simulated by using Computational Fluid Dynamics (CFD). A 3D modelling of rotary drum dryer including ambient air was created by considering transient simulation. The temperature distributions on rotary drum dryer surfaces of experimental setup during heating detected by using infrared camera were given to be boundary conditions of modelling. The average temperature at the surface of the drum lids was 80°C, and the average temperature on the heated surface of the drum was 130°C. The results showed that the internal temperature of air in drum modelling was increased relating on time dependent. The final air temperature inside the drum modelling was similar to the measurement results.

## 1. Introduction

Oil palm is an edible of vegetable oil extracted from mesocarp of oil palm fruit in throughout several processing. This kind of raw material was mostly planted in Southeast Asia, such as Malaysia, Indonesia, and Thailand. After harvesting process, fresh fruit bunch must be processed directly to milling factory not more than 24 hours. Sterilization process plays important role in oil palm factory processing [1]. The purposes of sterilization process are to soften the fruit, enzyme inactivation, reduce water content in fruit and facilitate oil extraction.

The sterilization process uses steam machines with the pressure applied at 40 psi (140°C) for 75 – 90 minutes [2]. From the process, grade A oil palm could be produced for consumption, such as pure vegetable oil. This kind of process consume a lot of water due to oil palm processing in the factory.

The second way to process oil palm is using batch dryer. This process does not require the steam as the first one. A batch dryer system can be placed in small factories. This process will heat oil palm by grilling. Hot air flow up by burning fuel, such as firewood or fuel oil. This kind of process needs much workers to flip oil palm from bottom to upper side. It resulted oil palm not cooked well and it took long time process around 30 hours (figure 1).

Umudee et al [3] studied about oil palm sterilization using microwave irradiation. It was found that sterilization of oil palm using microwave at 50°C is the optimum temperature for heating oil palm. But, for this kind of irradiation heating process is limited to industrial for future used. Noerhidayat et al [4] investigated about oil palm sterilization using high pressure. It proved that at 70 psi (temperature of about 150°C) for 30 minutes showed better in sugar content, release more oil and absorb more water.

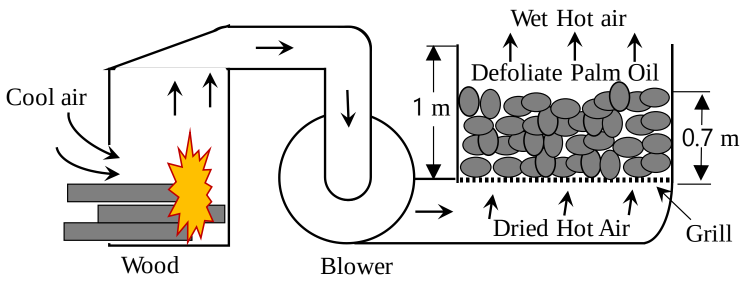


**Figure 1.** Grilling pattern of oil palm in factory

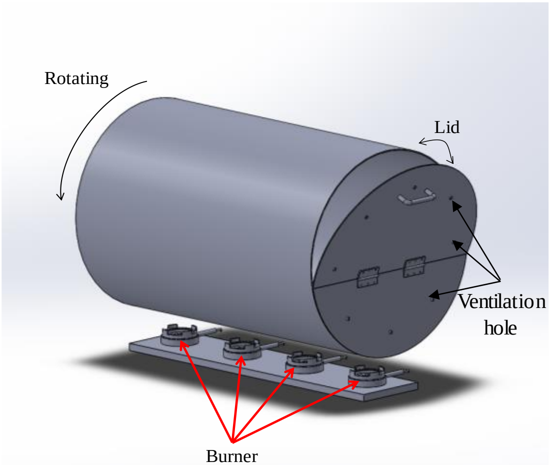


**Figure 2.** Model of rotary drum dryer.

Rotary drum dryer is being developed as a new tool for drying of medicinal and aromatic plant [5] which is to reduce specific drying energy consumption, keeping good quality and accelerating drying process. Temperature inside in rotating drum is important factor in drying, which depend on the amount of ventilation holes of rotating drum (figure 2). Therefore, the aim of this research was to understand behavior of the temperature inside the rotating drum by using CFD analysis.

## 2. Method

### *2.1 Rotary Drum*

The rotary drum dryer made of metal sheet with thickness of 3 mm. The dimensions of the drum was 90 cm in length and 57.5 cm in diameter. It is set on the structure which is supported by the bottom roller. The motor with gear that installed on the side of the drum rotates the rotary drum dryer. For the experiments, the fresh fruit palm in the drum is heated at the bottom rotary drum, which use LPG as fuel sources of thermal energy.

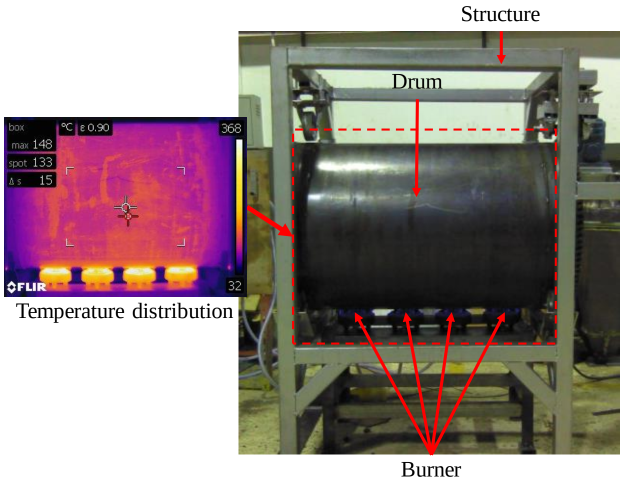


**Figure 3.** Appearance of temperature distribution on the drum surface using infrared camera.

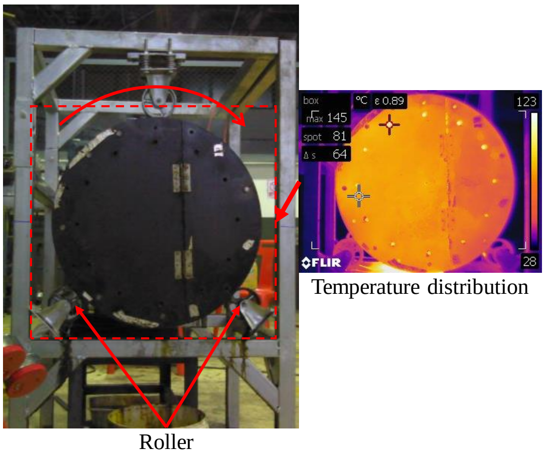


**Figure 4.** Appearance of temperature distribution on the cap surface of drum using infrared camera.

The figures 3 and 4 above shows the temperature on the surface of the rotary drum dryer and the cap of the drum which in steady conditions. The temperature at the surface of the cap was about 80°C and the temperature of the drum surface was about 130°C. The rotating drum was heated from the combustion of fuel LPG by the direct contact with the drum.

*2.2 Simulation model and grid generation*

ANSYS Fluent ver. 15.0 was used to simulate the flow characteristics. A 3D numerical model based on the finite-volume method was adopted to solve governing equations with boundary conditions. The geometry of the numerical model was the same as that of the experiment and this model of the rotary drum dryer in CFD will be reduced 10 times from actual dimensions shown in figure 5.

The details of the generated grid are shown in figure 6. The cutting plane along the centerline of the drum is shown to expose the internal grid system. The majority of elements were even rectangular. The simulation was analyzed with four elements cases and 1.2 millions cases and 1.57 millions cases are in the same trend. Therefore, 1.2 millions elements case was considered in this simulation.

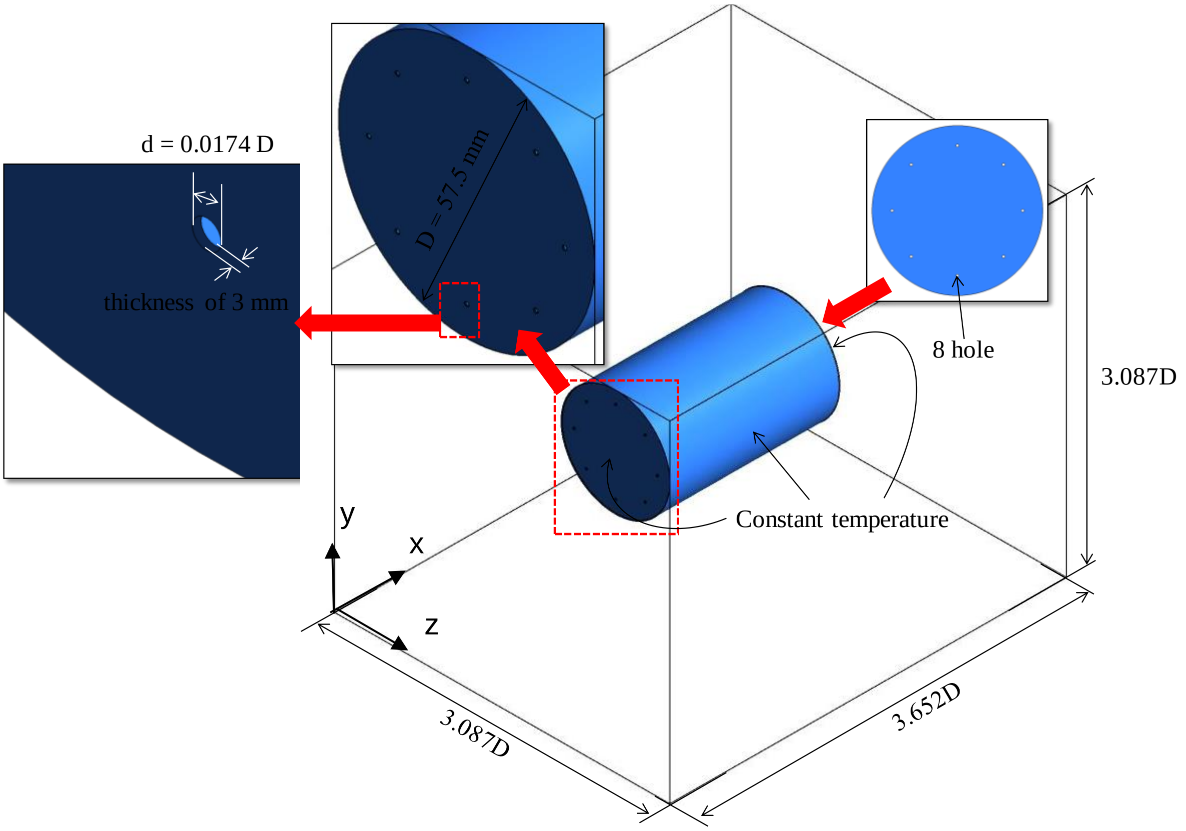


**Figure 5.** Model of rotary drum including surrounding air

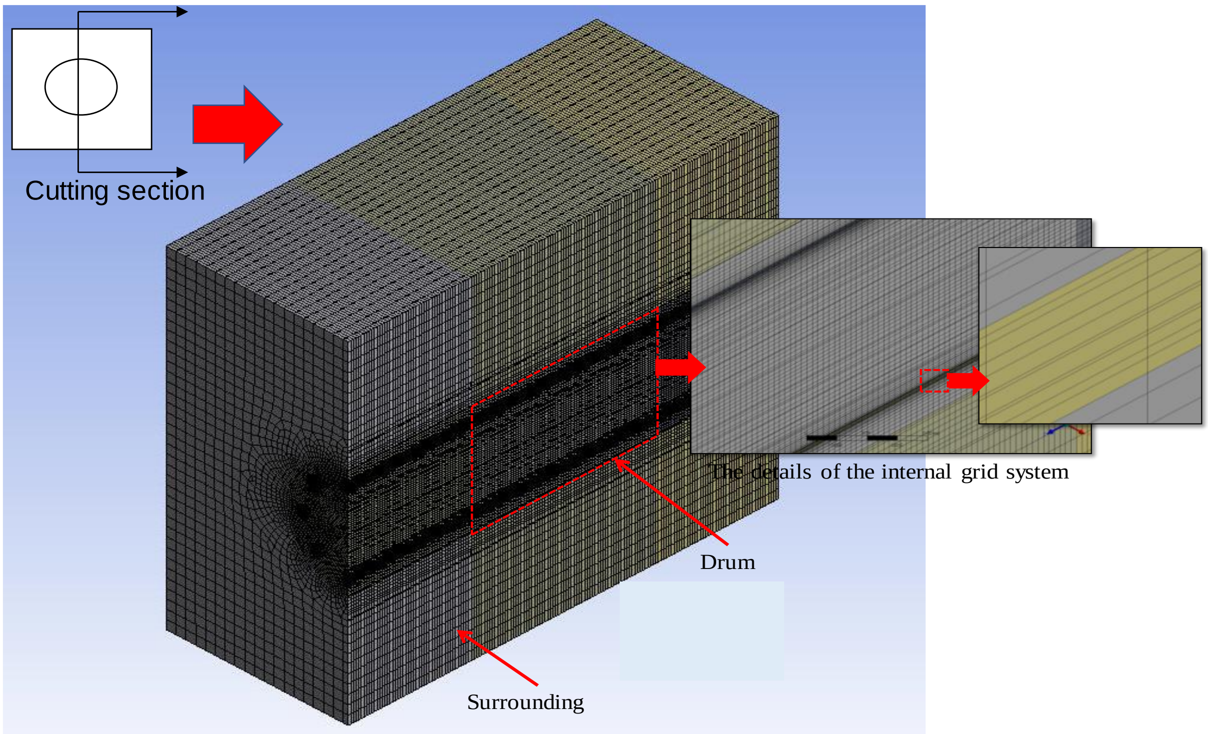


**Figure 6.** Internal Grid System.

The boundary conditions were identically specified to the experiment. For the rotary drum dryer, the number of hole was introduced. The details of the boundary condition are specified in table 1.

**Table 1.** Details of boundary conditions.

| Conditions | Setting |
|---|---|
| The temperature of drum dryer | 400 K |
| The temperature of drum dryer lid | 353 K |
| The temperature of environment | 303 K |
| The pressure of the environment | 1 atm |

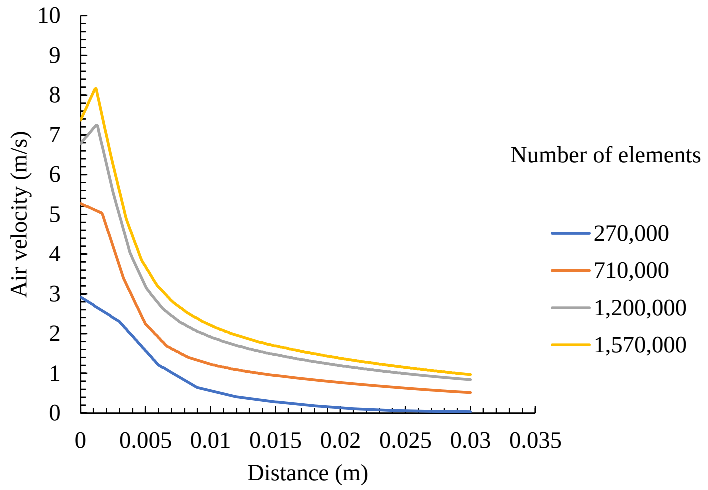


**Figure 7.** The effect number of elements on air velocity of the centre of ventilation holes to the surrounding

*2.3 Calculation Method*

A solution method was based on the SIMPLE algorithm with a second-order upwind for all spatial discretizations. The solution was considered to be transient. It was operated until the temperature in the middle of the drum dryer to the steady state. We set the timer to run transient which time period to calculate out as 2 seconds on each occasion, or called time step size was 2 seconds and each period will repeat it for 20 times. It has a number of calculations 1200 times or called numbers of time step is 1200. Therefore, it has the total time in 2400 seconds.

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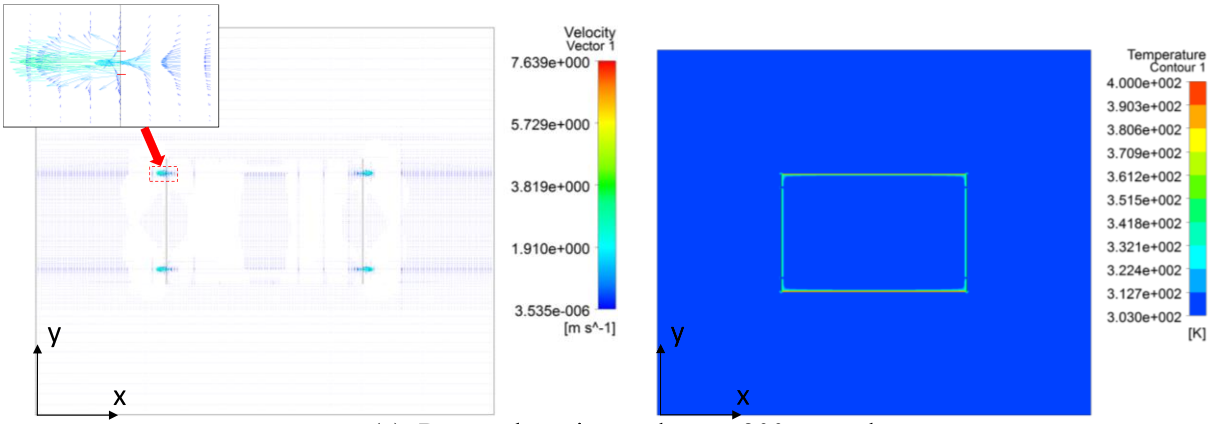
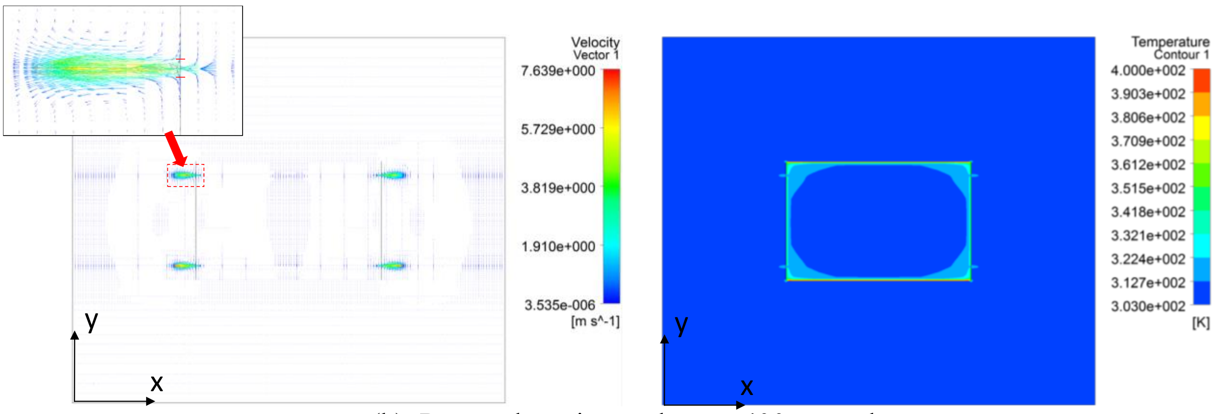
## 3. Results and Discussions

Temperature distribution and velocity vector profile was analysed with various time in xz plane at centre line cross section of rotary drum model (figure 8). At temperature 400 seconds, the temperature distribution was increase slowly from the edge side of rotary drum. At the same time, the velocity flow was also increase compare with 200 seconds case. According to the theory, volume at air is directly proportional to the temperature, so the airflow inside the rotary drum was pass through the hole. When the time become longer, the flow velocity also higher. Near outside of hole orifice the highest velocity value was found because of the pressure gradient of hole.

At 1000 second, the higher temperature distribution was found, above section of rotary drum while the bottom section was lower. For velocity, flow in above section showed stronger than below section of the rotary drum. Then for 1200 seconds, temperature distribution was the highest for whole surface of cross section of rotary drum. Near the hole of bottom section, it was showed non uniformed of temperature distribution.

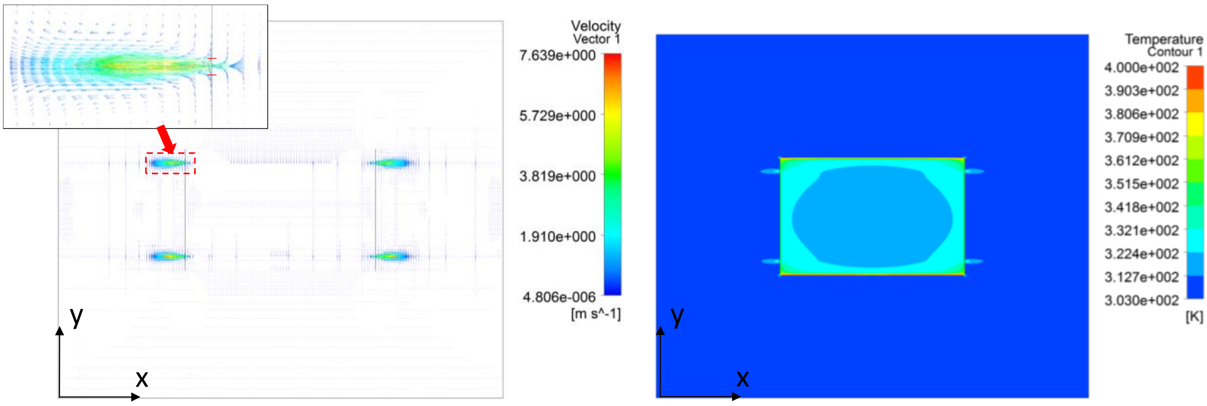



(a) Rotary drum in xy plane at 200 seconds.

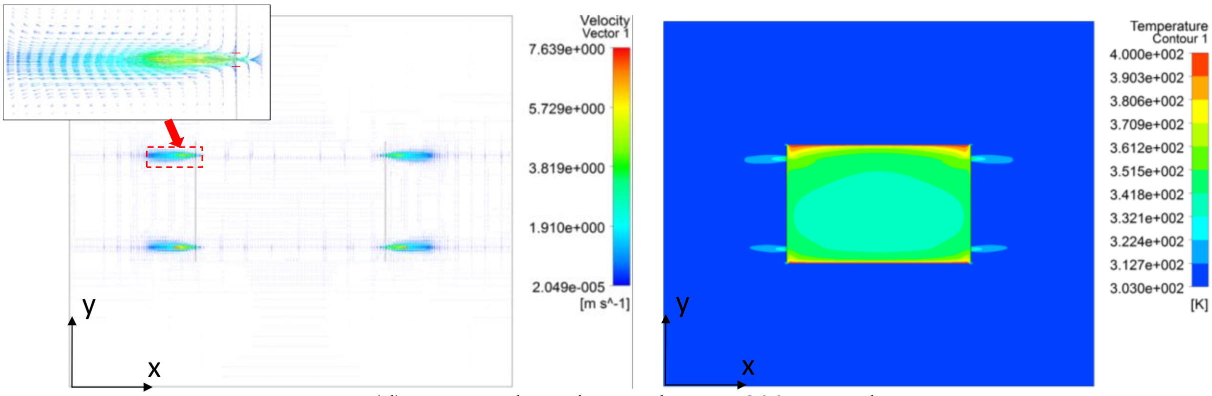



(b). Rotary drum in xy plane at 400 seconds.

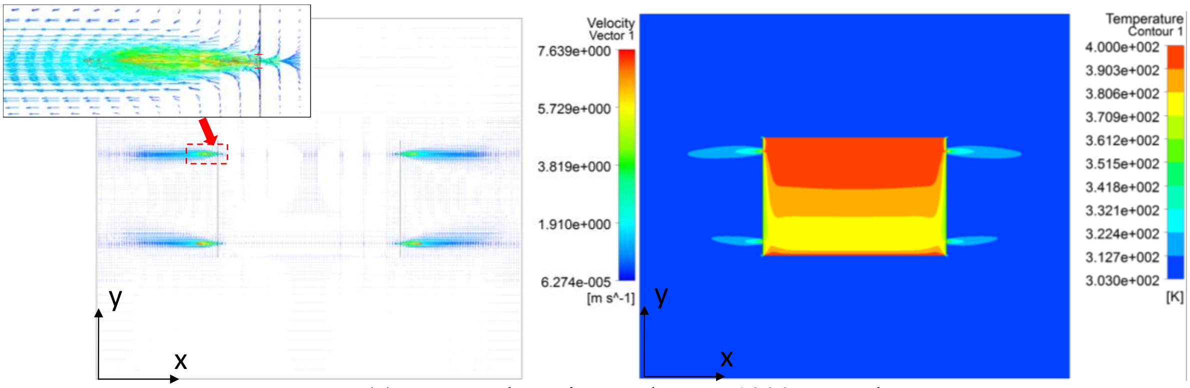
**Figure 8.** Velocity vector profile and temperature distribution of rotary drum in xz plane at various time.




(c). Rotary drum in xy plane at 600 seconds.

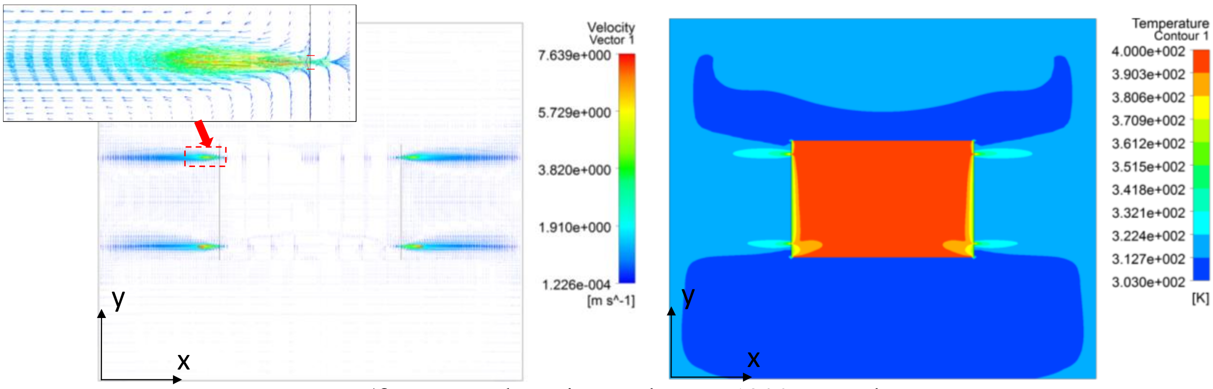



(d). Rotary drum in xy plane at 800 seconds.




(e). Rotary drum in xy plane at 1000 seconds.

**Figure 8.** Velocity vector profile and temperature distribution of rotary drum in xz plane at various time (continued)




(f). Rotary drum in xy plane at 1200 seconds.

**Figure 8.** Velocity vector profile and temperature distribution of rotary drum in xz plane at various time (continued)

## 4. Conclusion

In this work, flow and temperature distribution of rotary drum was analyzed at various times using CFD simulations. The highest and more uniform temperature and flow velocity distribution was found in 1200 seconds for this work. The results was analyzed with fix hole and constant time range (200 to 1200 seconds). For further study about different hole and more temperature range will be analyzed for temperature and velocity flow of rotary drum.

## Acknowledgement

The research grant was supported by Energy Policy and Planning Office (EPPO), Ministry of Energy, Thailand, grant No. EE-PSU-59-02, PERIN (PSU Energy System Research Institute), ETRC (Energy Technology Research Centre), and Faculty of Engineering, Prince of Songkla University.

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**APPENDIX 5**

The development of rotary drum dryer for palm fruit sterilization

(Published in *IOP Conference Series: Materials Science and Engineering 297(1),012031*)

# The development of rotary drum dryer for palm fruit sterilization

# The development of rotary drum dryer for palm fruit sterilization

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**Abstract**. The aim of this research was to design and develop a rotary drum dryer for palm fruit sterilization. In this article, the results of the effect of ventilation hole number on the reduction of moisture content in palm fruit were presented. The experimental set up was a drum dryer which has 57.5 cm in a diameter and 90 cm in a length (the size was similar to 200-littre steel drum container). A driving gear and a gear motor rotated the drum dryer. The ventilation hole were drilled on the lateral side of the drum. The diameter of ventilation hole was 10 mm, and the number of ventilation hole were 18, 36 and 72 hole (each side was 9, 18 and 36 hole, respectively). In the experiment, the palm fruit was dried by using LPG to burn and heat the bottom of the drum. The flow rate of LPG was controlled to keep the temperature inside the drum steadily at 120°C.

## 1. Introduction

Oil palm is economic crop in many countries such as Indonesia, Thailand and Malaysia. It could provide mean income and economic development for living people. Oil palm could use 71 percent for foods (margarine, processed food, chocolate, etc), 24 percent for consumer products (cosmetics, detergents, candles, etc) and 5 percent for energy uses (electricity, heating fuels, etc). Oil palm become raw material for many kind of purposes because of its high pressure oxidation resistance, capability to dissolving chemicals insoluble, high coating power and does not irritation to the body for cosmetic uses.

Oil palm industry undergo two type of processes, the first one is the steam process which uses steam of 140°C for 75 – 90 minutes to stop free fatty acid formation and to soften the palm [1]. In this process it produces crude oil palm (CPO) and crude palm kernel oil (CPKO). Crude oil palm is obtained from mesocarp in orange color of oil palm while for crude palm kernel oil is came from kernel in the nut in white color. Crude oil palm is processed at oil palm milling machine and kernel were removed from nut is kind of byproduct of oil palm milling machine.

The second process is the batch sterilization that is mostly used in small factories. Mostly small factories in Thailand accept falling/defoliate fruit from farmers. That kind of falling fruit/defoliate fruit separated from fresh fruit bunch. During batch sterilization, oil palm was heating. This process will heat by grill. Hot air flow up by burning fuel, namely firewood or fuel oil (figure 1).

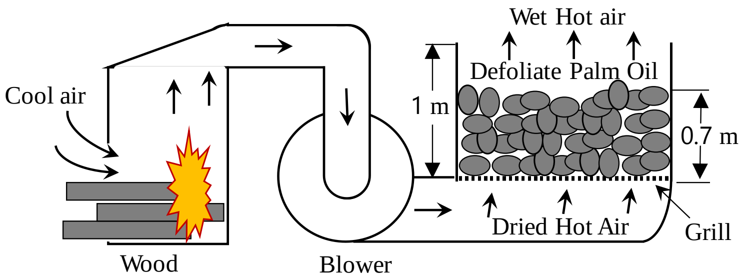


**Figure 1.** Grilling pattern of oil palm in factory

In the grilling process, several problems have been found in that oil palm was burned due to exposure to direct fire and not heated well. The palm fruit on the ground layer is dried faster than on the upper layer. During grilling process, workers should flip the oil palm from ground layer to the upper layer. In addition, it takes about 30 hours to dry oil palm fruit.

This kind of problem could be solved by designing a rotary drum dryer as shown in figure 2. The falling palm fruit is put into a rotating drum. Then it will be heated from below site. In commercial use, the heating fuel may be firewood. The rotating drum will rotate slowly. The oil palm is mixed together in rotating drum, which will transfer heat to oil palm fruit.

In past, rotary drum principle has been applied to herbal steam [2] however but the baking bin was sieve. This will lose a lot of hot air. In addition, Computational fluid dynamic (CFD) in study of particle dispersion behavior in rotary drum has been used [3]. The purpose of this research was to develop a rotary drum drying of oil palm, which has the advantage: (1) the drying oil palm not expose to smoke, (2) the drying oil palm is mixed in lower layer and upper layer. During drying process, the fuel of rotary drum are LPG. Initially, the effect of number 18, 36 and 72 (two sides) ventilation hole of the rotary drum on the moisture content of the palm fruit was studied.

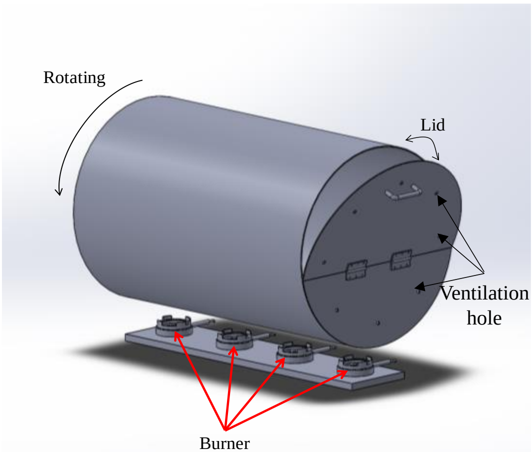


**Figure 2.** Rotary drum model

## 2. Method

### *2.1 Experimental design*

Figure 2 show prototype of rotary drum dryer used in the experiment. The rotating drum is made of sheet steel and rolls into a cylindrical shape. With a diameter of 57.5 cm and a length of 90 cm, the rotary drum is mounted on four supported bearings, with one top roller located opposite the drive gear. It serves the drum to rotate in a fixed position.

The roller on top and the gear set pressed with the spring set to adjust the press on the drum. The side of rotating drum has a gear set and a gear motor. It could adjust the rotation speed of the rotating drum

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using the inverter. The rotary drum slowly rotated at 1.68 rev/h and 8.34 rev/h to prevent palm fruit bruise from contusion that result in high FFA.

*2.2 Experimental methods*

Figure 3 shows a diagram of a rotary drum design. Oil palm fruit 50 kg dried for each batch. LPG was used to burn at the bottom of rotating drum by placing the four gas stoves at the bottom of the rotating drum, which directly heated.

In addition, a rotameters installed to measure the flow rate of LPG fuel for controlling the temperature inside the drum. Every gas pipe in the experiment controlled the flow rate of LPG fuel in order to keep the temperature inside the rotary drum constantly at 120°C (±3°C).

The 50-kg oil palms were load into the drum for drying. The 200-g oil palm sample was put into the small grill. This 200-g oil palm sample was included in those 50-kg oil palms. After finishing the drying, the 200-g oil palm sample was dried again in electric oven to evaluate the dry matter of the oil palm. During drying process, the drum including oil palm was weighed every 1 hour to evaluate moisture content of the oil palm. A data logger which was rotated together with drum was used to detect temperature inside the drum. The parameters in this study were (1) rotating speed of drum at 1.68 rev/h and 8.34 rev/h and (2) ventilation hole number (for releasing moisture) at 9, 18 and 36 for each cap of the drum.

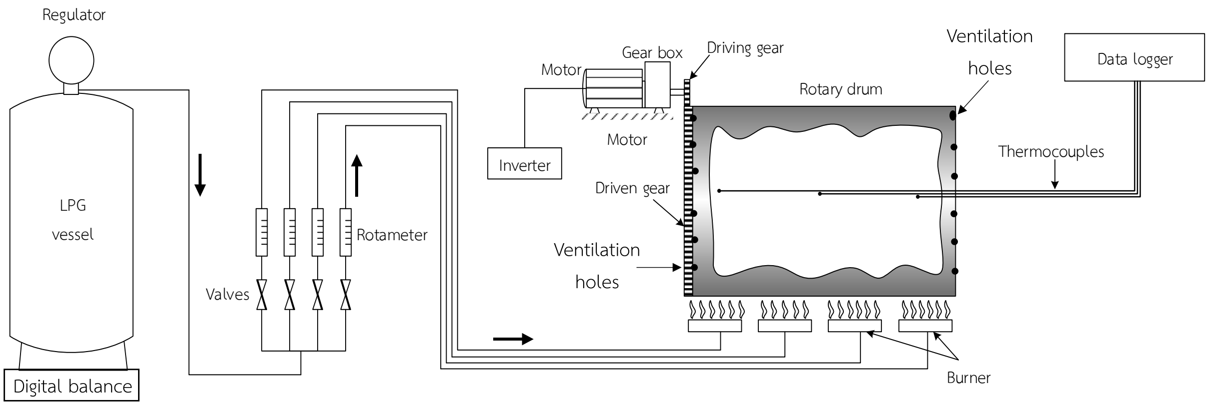


**Figure 3.** Rotary drum experimental setup

*2.3. Calculation of moisture content and moisture ratio*

Percentage of moisture content (kg of water/kg of dry matter) was determined using the following equation:

$$\%MC\ (db) = \left(\frac{W - D}{D}\right) \times 100 \quad (1)$$

where W is weight of sample at every time, D is the dried weight of oil palm. In drying experiment, the initial moisture content compared to the different conditions. The moisture ratio is derived from following equation:

$$MR = \frac{(M_t - M_{eq})}{(M_{in} - M_{eq})} \quad (2)$$

where $M_t$ is the moisture content at time of drying, $M_{eq}$ is final percentage of moisture content, $M_{in}$ is initial of moisture content.

## 3. Results and Discussions

Figure 4 shows the effect of ventilation hole and rotating speed on the moisture content at different times. The results showed trend that various drying period of oil palm sample weight decreased. There is small effect of the number of ventilation hole and rotating speed, because of moisture content inside drum. Rotating speed of 1.68 rev/h with ventilation hole of 18 and 9 indicated similar trend but after 6 hours the temperature was increase. The initial moisture content was 12.69 % and reduced to 10.18 % and the ventilation hole 9 the moisture content reduced from 11.52 % to 7.25 % respectively.

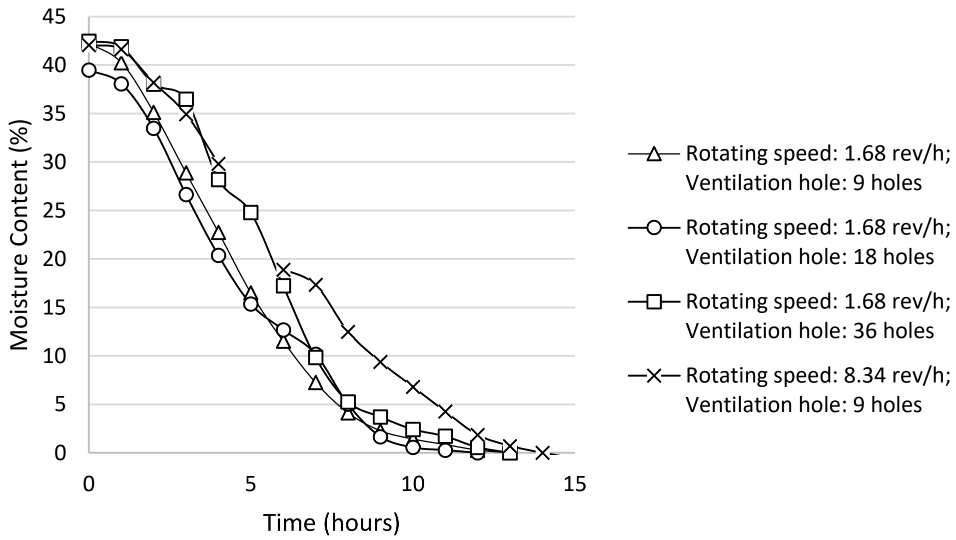


**Figure 4.** Moisture content of each cases

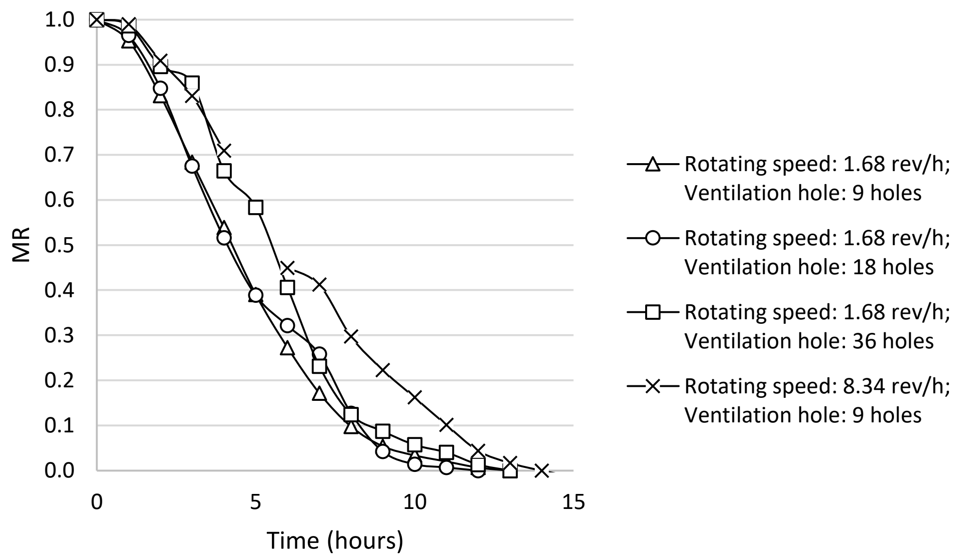


**Figure 5.** Moisture ratio of each cases

The moisture content of rotation speed 1.68 rev/h with ventilation hole of 36 and rotating speed of 8.34 rev/h and ventilation hole of 9 it also changes due to temperature changes at 6 hours of drying. The initial moisture content was 17.23 % to 9.82 % followed by moisture content of rotary speed of 8.34 rev/h and ventilation hole of 9 also decrease from 18.89 % to 17.33 %. When the drying process throughout passed 12 hours, it was found that, the sample weight dropped almost linearly then almost constant. In addition, LPG fuel consumption per hour in each cases ventilation hole of 36, 18, 9 namely 0.53 kg, 0.61 kg, 0.61 kg, while for rotating speed of 8.34 rev/h with 9 ventilation hole case was 0.56 kg. For drying process, it took about 13-14 hours for changing the color from yellow to brown and palm kernel from white to colorless.

## 4. Conclusion
In this research, the effect of ventilation hole and rotating speed of rotary drum dryer were studied on moisture content and moisture ratio of oil palm. According to this study, it has been found that for all ventilation hole and rotating speed showed small effect of moisture content and moisture ratio of each cases. For the lowest fuel consumption is case ventilation hole of 36 which is 0.53 kg per hour. This kind of visual appearance oil palm represent that oil palm could proceed to screw pressure machine. For drying in real factory, it takes up to 30 hours to achieve this condition. However, this article presents only preliminary result. This is needed further study for energy cost of drying process compare to factory.

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