Analytical Study and Fabrication of a Solar-Based Dryer for Pepper-Drying (Agricultural Product Drying)

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ABSTRACT

Sarawak has fertile slopes and an optimum environment for pepper cultivation. The state produces the majority of pepper products in Malaysia and contributes to multimillion agricultural export earnings every year. The pepper cultivation in Sarawak relies on smallholdings and there were no large-scale plantation nor estate recorded so far. The majority of farmers exercise natural sun drying to produce the peppercorn as this method is simple to implement at low cost. However, it does not guarantee stable output quality and quantity due to unpredictable weather conditions and massive labour effort.

This report explores a workable passive solar dryer that will work well in tropical rainforest climate for local pepper smallholdings. It utilises existing technologies from different applications and optimise for small quantity peppercorn production. It also features low cost and sustainability. The dryer is simple to operate, mobile, requiring no artificial power assistance and is capable of drying peppercorns at targeted weather condition.

The design of the solar dryer is based on pressure differential stack effect and fluid flow optimisation to ensure optimum condition in the drying chamber. The design was implemented and tested in open field for characteristics studies. Experiments done have shown the dryer will work satisfactorily in tropical climate from sunny days to mixed weather to rainy days and even on a cold wet night. Although some adjustments on the dryer (adjusting chimney height) are needed for different weather conditions, the dryer has, in general, given a satisfactory performance. It has proven to be able to boost the throughput with acceptable quality with the least possible human effort.

The design has proven working for peppercorn production from this research; yet some modifications can be done to further enhance the achievement, it includes: weight reduction and heat flow optimisation at dryer inlet for more even drying.

ACKNOWLEDGEMENT

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Last but not least, I wish to express my deepest gratitude to Malaysia Pepper Board who had kindly offered huge assistance in financial, test samples and support facilities, as well as their efforts and precious time to my studies. The research would not have gone so smoothly without the funding, dedicated staff and facilities.

DECLARATION

I declare that this thesis contains no material that has been accepted for the award of any other degree or diploma and to the best of my knowledge contains no material previously published or written by another person except where due reference is made in the text of this thesis.

LUK TIEN BOH
June, 2013

PUBLICATIONS ARISING FROM THIS MASTER'S STUDY

Vakhguelt, A, Chai, A, Luk, TB & Chong, CJ, 2010, “Extending the Drying Capability Utilising Nature Airflow Booster for Convective Solar Dryer”, *Proceeding of 19th International Congress of Chemical and Process Engineering*, 28th August – 1st September 2010, Prague, Czech Republic, Org. Number H6.6.

Vakhguelt, A, Chong, CJ & Luk, TB, 2009, “Experimental Study of Drying Fresh Pepper Berries In a Solar Dryer”, *Proceeding of the 7th World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics*, 28th June – 03rd July 2009, Krakow, Poland, pp. 1239-1245.

Luk, TB & Vakhguelt, A, 2009 “Automating The Solar Dryer – Airflow Control Utilizing Pressure Difference Concept”, *Proceeding of the Global Conference on Power Control and Optimization (PCO'2009)*, 1st - 3rd June 2009, Bali, Indonesia, Ref. Number E16.

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CHAPTER 1: INTRODUCTION

To ensure availability of seasonal food all year round, preservation techniques are crucial. In fact, human beings do not need to struggle for their life due to hunger, especially during unfavourable weather conditions or physical migration by consuming preserved food. There are a few different techniques in food preservation; each method used in preserving the food depends on different factors like culture, location and development of the society. For example, natural sun drying is usually done in hot climate countries and freezing technique is done during the winter in countries with continental climate. Proper preservation and storage allows food to be kept for longer period for self-consumption and for trades. Nowadays, preserved food is also an alternative source of income for many people who are involved in the food business. Due to the growth of world population, food preservation has been done on a massive-scale and many new techniques were invented or developed. The preserved food is now not only for local consumption but very often it is shipped globally to become a multi-billion export-import business.

Preservation can be done in many ways and each method brings different outcome and 'shelf-life' to various sources of raw food. One of the conventional techniques is drying. Drying prolongs the food storage period by reducing the rate of decay within the organic substance. The idea is rather simple. Since the decaying process occurred usually in moist surroundings, the decaying process can be effectively slowed down by eliminating the optimum environment for it. In brief, the drying process is referred to the course of removing water content from the raw food so that the internal organic substance, ideally, will never metamorphosed into other substances in which, it is referred as deterioration.

Food drying is always seen as easy and simple to perform; yet in fact if one does look into the general recovery rate of the dried bits, it often brings to disappointment. As their earnings are depending on both quantitative and qualitative means and not either, low quality and quantity outcome means the producers are losing their income. Therefore, the first problem is how to get the optimum weight out of the wet raw bits at acceptable quality. Over-dried product has lower weight which leads to reduction in total earnings. On other hand, if the product is not dry enough to avoid mould growth within the acceptable timeframe (shelf-life), the value will also depreciate rapidly. In qualitative point of view, mould growth is just one of the issues; different raw food product contains different organic substances that may cause adverse transform. Therefore, how to dry the agricultural products without losing too much original features like taste, aroma, vitamins, and enzymes will then be the main concern.

1.1 Introduction

In the case of spice preservations, natural sun drying have been extensively practised in most developing countries to preserve the raw spice. Spices, like most vegetables, cannot sustain elevated temperatures without losing its flavour. Therefore, it is less likely to be preserved well using traditional smoke technique which is applicable to meat and fish products. High level of heat will breakdown the thin cell-wall and cause it to lose its important substances to the surrounding and this makes the dried bits worthless. Natural sun drying method is simple and requires almost no cost to operate. Besides, it can be carried out at almost any place regardless of the region and terrain as long as the work-space is well exposed to the sun rays.

Natural sun drying does have limitations. Since the method uses natural source of energy, it is subjected to climatic change of that particular local region; it includes seasons, instantaneous radiation flux, cloud cover, rainfall, humidity level and windiness of the region at a given time period. Basically, the heat source is gained from the solar radiation in the form of direct, diffused, and reflected rays. It heats up the raw bits and the surrounding environment to initiate the drying process. The mass transport of saturated air is then displaced by buoyancy of heated-air or so called natural convection and forced convection resulted from massive air-exchange at the atmospheric surrounding from time to time, like breeze. In reality, the optimum drying condition will fade away if some circumstance happens in the atmosphere, for examples:

(1) High relative humidity (RH): it will reduce the water holding capacity and cause slower surface evaporation

(2) High index of cloud cover: it means too much cloud blocking the radiation falling directly onto the raw bits and thus slows down the drying force due to lower operating temperature.

(3) Unexpected rain fall: it will directly moisturise the raw bits and may cause early deterioration due to rehydration.

(4) Strong wind: it will lead to loss of light-weight finished product (been blown away) and loss of temperature at the environment of product surface.

In some cases, case-hardening will happened due to high evaporation rate at the surface which blocks the channelling of fluid from the inner body to the surface before it is removed. This condition promotes risk in mould growth since the inner part is still wet enough to support the growth of microbes.

Next, natural sun drying is also subjected to disastrous attacks and contamination by natural survivals in the region like birds or insects (Madhlopa *et al*., 2002). For living creatures other than human, those spices to be dried or the dried product are considered something that can be consumed. Other threats include physical disruption or damage, introduction of foreign matters like bird droppings and et cetera. This could directly result in a loss to the final recovery of the dried product.

The issues mentioned above may be predicted, but they are not totally controllable. For example, general weather condition is predictable in macro-scale but partial region in the forecasted area may experience quite a different condition. The affected area may suffer a sudden change in considerably short period of time. These changes can be flash rain, unstable radiation flux and air current. In addition, no one is able to predict when a bird may fly pass the top of the drying mat and leave some droppings. However, if the farmers did carefully guard the perimeter of the work-space, this issue can be minimised.

1.2 The Pepper Variety and Cultivation in Sarawak

Black pepper is one of the most widely used spice in the world. In Malaysia, it is referred to a processed product from the fruit of the climbing vine of Piperaceae family which is believed to being originated from south-western India. Technically, the exact species cultivated in the country is called Piper Nigrum L. This pepper species usually blooms healthily in warm and wet tropical rainforest climate. Now, Malaysia is still one of the key exporters of black and white pepper in the world.

1.2.1 The Variety of Sarawak Pepper

Black Pepper or Piper Nigrum L. is believed to have been cultivated in Malaysia since 17th century and the majority of cultivation is in the state of Sarawak (Ravindran, 2000). Nonetheless, official record in the local books shows that the cultivation is only dated back to 1856. Chih and Sim (1977) stated that the Department of Agriculture Sarawak (JPS) had collected twenty-four species of Piper and nine species of cultivars of Piper Nigrum L. (including the early Kuching and Sarikei cultivars) in its research centre at the time they composed the technical bulletin in 1977. Research was done with the intention to yield a better species.

In recent years, the Department of Agriculture Sarawak has confined their scope and recommended only three cultivars to the farmers, they are: Kuching, Semongok emas (released in 1991), and Semongok aman (released in 2006). These cultivar species have the advantages over others in terms of high production and better tolerance to pepper diseases. In general, the later one is aimed for premium black peppercorn and green pepper because of the richer chemical content. Whist, the Kuching species is intended for white peppercorn because of its thinner pericarp and comparatively bigger berries that yields higher returns in ratio.

1.2.2 The Cultivation and Production of Sarawak Pepper

Sarawak has fertile slopes and optimum environment for pepper cultivations. In fact, majority of pepper production in Malaysia is cultivated in Sarawak in which, it contributed to an official figure of 98% (Paulus *et al.*, n.d.) to total production in the country. Besides, it is one of the most important agricultural export earners.

Pepper cultivation in Sarawak is heavily dependent on smallholdings (refer to Figure 1.1). Practically, there was no large-scale plantation or estate recorded in government books (Department of Statistics Malaysia, 2000). They are mostly populated in Kuching, Sri Aman and Sarikei Division (near to Sibu) which is the southern region of the Sarawak state. There are also some productions in middle-to-northern region (Miri Division). The final production is mainly based on the efforts of Malaysia Pepper Board (MPB) working together with local merchants who exercises the collection, packaging and markets of peppercorn in specific regions. In relation to export of pepper, MPB is the main promoter and the owner of facilities that helps in determination of segregated qualitative assessment of the final product.

Figure 1.1a: Typical Pepper Farm Possessed by Smallholdings on flatland (Tebedu area, Kuching Division)

Figure 1.1b: Typical Pepper Farm Possessed by Smallholdings on Slopes (Borneo Heights, Kuching Division)

1.3 The Economic Influence of Sarawak Pepper

Sarawak pepper is mainly cultivated for export purposes. More than 90% of the recorded figures are aimed for the global market which contributes to millions of dollar to the state income. Table 1.1 shows the twelve-year continuous official report readings since 1998.

From Table 1.1, it shows that the average production quantity is declining in recent years. It is due to the depreciated market price for pepper products which is caused by the increase of more promising competitors in the global market. In 2010, Malaysia was ranked at the sixth-place as the world largest producer of Black Pepper and related products as officially announced by Malaysia Investment Development Authority (MIDA). This is due to the fact that the industry was populated dramatically with new investors who finance some large-scaled pepper plantations since the last few decades. Currently Vietnam has become the main player in this industry, supplying around one-third of the world consumption for various pepper products.

Table 1.1: The Twelve-year summaries of land use and export figures for Peppercorn produced in Sarawak (Information adapted from Yearbook of Statistics Sarawak 2002-2010).

Year	**Smallholding[1] Cultivate Area**	**Total Production for Export (Black + White peppercorn)**	**Total Income from Export**
	Area in Hectare (Total black & white peppercorn in '000 tonnes)	Quantity In Tonne	Value in RM '000
1998	11,373 (14.2+4.8)	18,888 (14,026 + 4,862)	365,482
1999	12,196 (15.5+6.0)	22,131 (16,324 + 5,807)	408,197
2000	13,327 (21.5+2.5)	24,033 (21,951 + 2,082)	365,787
2001	13,555 (23.4+2.6)	25,897 (23,439 + 2,458)	177,983
2002	13,862 (21.6+2.4)	23,225 (20,847 + 2,378)	138,517
2003	13,533 (17.5+3.5)	19,379 (16,045 + 3,334)	124,433
2004	12,930 (16.5+3.5)	19,980 (16,802 + 3,178)	116,233
2005	12,673 (16.0+3.0)	18,508 (14937 + 3,571)	115,592
2006	12,268 (15.5+3.5)	16,684 (12,355 + 4,329)	135,984
2007	11,849 (16.3+3.7)	15,023 (11,237 + 3,786)	177,481
2008	11,298 (15.4+6.6)	12,353 (9,959 + 2,394)	153,751
2009	10,889[2] (15.3+6.6)	13,111 (10,544 + 2,567)	144,809
2010	Nil (16.9+7.3)[2]	6,125 (5,053+1,072) <Jan-June>	77,889 <Jan-June>

[1] There is no pepper estate in Sarawak; Smallholdings is refer to lands, contiguous or non-contiguous that aggregating less than 100 acres (40.47 hectare) in area, planned with crop under a single legal ownership.

[2] Estimated value based on figures from first two quarters.

Nonetheless, Sarawak pepper product is famous for its natural quality, aroma and pungency. The uniqueness of the Sarawak Pepper has gained its niche in the current competitive market which makes Malaysia stood up well in the industry even it is yet to be able to compete in terms of quantity. Now, the main issue should then be questioning how the production throughput can be increase so that more revenue will be generated out of the available raw products.

1.4 The Practicality of Solar Dryer in Tropical Rainforest Climate

Tropical rainforest generally gives the impression of lush green under hot and humid weather with frequent downpours. Lots of different vegetation can be cultivated easily without much effort needed. Nonetheless, such climate does not favour steady and fast drying of the agricultural products if natural sun drying method is preferred. To achieve more effective drying, consistent hot and dry environment is needed to promote surface evaporation more effortlessly.

Preliminary studies were done in the main pepper production regions to investigate the condition of the surroundings. It aimed to explore a loophole of the existing dryers so that a better system can be designed for the sake of the local farmer. Meteorology parameters of specific points were obtained from Department of Meteorology Malaysia, Sarawak Branch (JMM Sarawak). Table 1.2 shows the meteorology data recorded from three different stations for analysis.

Table 1.2: Meteorology data collected from different regions for analysis

Area Investigated	**Kuching Division**	**Sri Aman Division**	**Sibu Division**
Station	Kuching Airport	Sri Aman Airport	Sibu Airport
Latitude	North 01º 29'	North 01º 13'	North 02º 20'
Longitude	East 110º 20'	East 111º 27'	East 111º 50'
Height Above M.S.L.	21.7 meters	9.6 meters	7.5 meters
Height Of Anemometer Head Above Ground	12.2 meters	-	-

The acquiring of meteorology data from JMM Sarawak is due to two reasons: First, the climatic behavioural studies will be more reliable if the amount of data can be dated back to an earlier period. Second, the main pepper cultivation areas in Sarawak are spread along the longitudinal axis in the geographic coordinate system (from Kuching to Sibu Division). Since the development and test of dryer will be performed in the Kuching area, therefore the analysis is done mainly based on Kuching source. Selected sources from Sri Aman and Sibu stations are presented to validate the projected working condition in the design consideration.

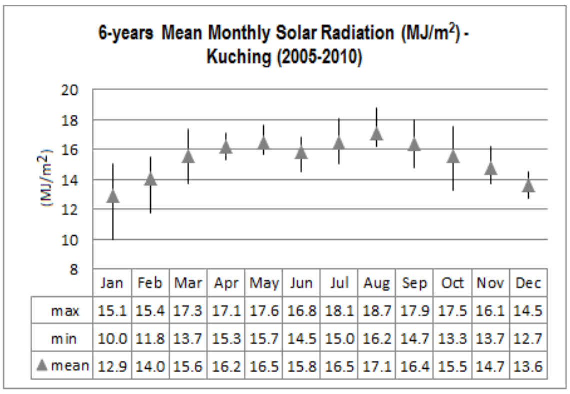
1.4.1 The Solar Radiation and Cloud Cover – Source of Operating Temperature

The main drying force of a solar dryer is the long-wavelength infrared rays. It is sourced from the solar radiation from direct, diffused, and reflected rays. Among those, the direct ray is the main contributor in heating perspective. The diffused and reflected rays will have much less effect. In other words, the operating temperature of a solar dryer will depend on total solar energy fallen onto the earth surface where the solar dryer is placed.

1.4.1.1 Solar Radiation

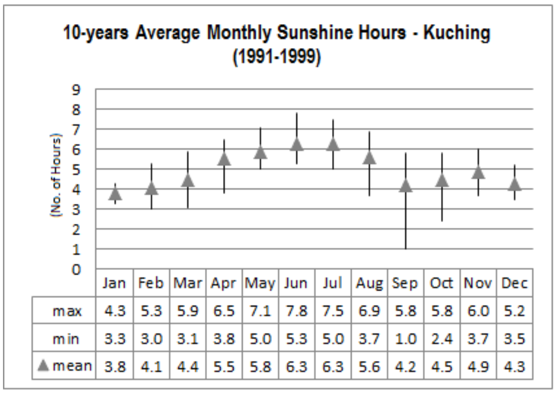
Solar radiation or irradiation is a representation of the summation of solar irradiance over a period of time, usually a day. It is useful in the design of solar energy collection system, like solar dryer, as it helps to tell how much heating energy is available to the system in a given operating period. JMM Sarawak started to upgrade its system to collect solar radiation only since 2005. Prior to that, it measured only the solar irradiance. Figure 1.2 presents the monthly average solar radiation with high-low data over six years period in Kuching area.

An annual mean of 15.4 MJ/m^2 is hitting the earth surface daily in Kuching area, which is above the average compared to most of the regions in the world. From Figure 1.2, it shows a quite stable average starting from the months of March until October. As the major harvesting period falls within the same period, it should have a favourable chance to use a solar dryer.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
max	15.1	15.4	17.3	17.1	17.6	16.8	18.1	18.7	17.9	17.5	16.1	14.5
min	10.0	11.8	13.7	15.3	15.7	14.5	15.0	16.2	14.7	13.3	13.7	12.7
▲ mean	12.9	14.0	15.6	16.2	16.5	15.8	16.5	17.1	16.4	15.5	14.7	13.6

Figure 1.2: 6-years Mean Monthly Solar Radiation (in MJ/m^2) in Kuching Area (previously is in kW/m^2)

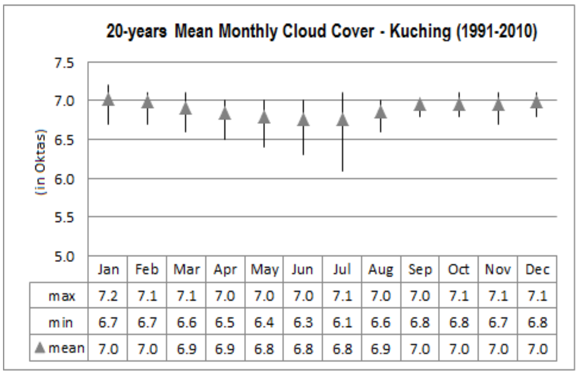


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
max	4.3	5.3	5.9	6.5	7.1	7.8	7.5	6.9	5.8	5.8	6.0	5.2
min	3.3	3.0	3.1	3.8	5.0	5.3	5.0	3.7	1.0	2.4	3.7	3.5
▲ mean	3.8	4.1	4.4	5.5	5.8	6.3	6.3	5.6	4.2	4.5	4.9	4.3

Figure 1.3: 10-years Mean Monthly Sunshine Hours (in hours) in Kuching Area (there is no more record after 1999)

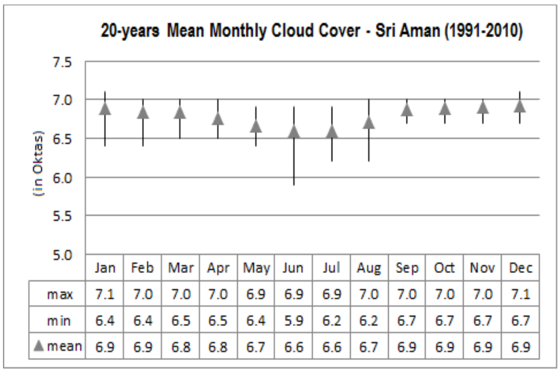
1.4.1.2 Sunshine Hours

On the other hand, viewing the sunshine hours of the region (figure 1.3), an annual average of daily five hours bright sunshine does depict the distribution of the instantaneous energy is not quite evenly distributed over a day even though Sarawak is located very near to the equator, which should experience about twelve hours of daylight daily throughout the year. The incident explains the solar collector at an instance and stay below optimum operating value at other times. For food drying, it is considered very unfavourable as there is a cap-temperature needed to be observed. From Figure 1.3, it seems the condition is not quite pleasing for peppercorn production at early time of the major harvesting period (March to April).



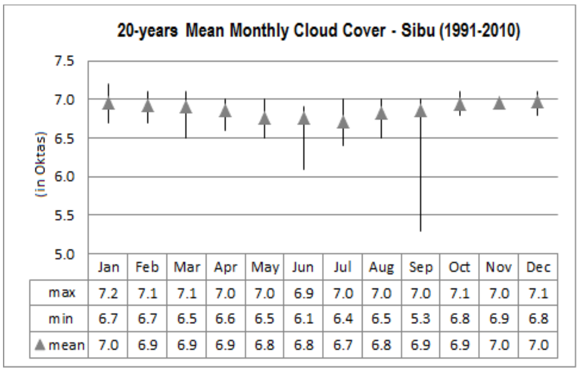
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
max	7.2	7.1	7.1	7.0	7.0	7.0	7.1	7.0	7.0	7.1	7.1	7.1
min	6.7	6.7	6.6	6.5	6.4	6.3	6.1	6.6	6.8	6.8	6.7	6.8
▲mean	7.0	7.0	6.9	6.9	6.8	6.8	6.8	6.9	7.0	7.0	7.0	7.0

Figure 1.4a: 20-years Mean Monthly Cloud Cover in Kuching Area.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
max	7.1	7.0	7.0	7.0	6.9	6.9	6.9	7.0	7.0	7.0	7.0	7.1
min	6.4	6.4	6.5	6.5	6.4	5.9	6.2	6.2	6.7	6.7	6.7	6.7
▲mean	6.9	6.9	6.8	6.8	6.7	6.6	6.6	6.7	6.9	6.9	6.9	6.9

Figure 1.4b: 20-years Mean Monthly Cloud Cover in Sri Aman Area.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
max	7.2	7.1	7.1	7.0	7.0	6.9	7.0	7.0	7.0	7.1	7.0	7.1
min	6.7	6.7	6.5	6.6	6.5	6.1	6.4	6.5	5.3	6.8	6.9	6.8
▲mean	7.0	6.9	6.9	6.9	6.8	6.8	6.7	6.8	6.9	6.9	7.0	7.0

Figure 1.4c: 20-years Mean Monthly Cloud Cover in Sibu Area.

1.4.1.3 Cloud Coverage

The cloud cover refers to the cloudiness of an area. The fraction of the clearness of the sky at stated area usually refers to a mean value over a day. The Figures 1.4a to 1.4c shown below are based on oktas unit. That means there is a full cloud cover if the value is eight oktas and half of the sky over a particular area is covered if the value is four oktas.

From the figures (1.4a to 1.4c), one can conclude that majority of pepper cultivation area do seldom experience a clear sky since the variation (min to max) is small. This shows limitation of the application of conventional solar dryer due to instability of main heating source – the direct radiation, as the cloud crowd is often causing the fluctuations in heating energy.

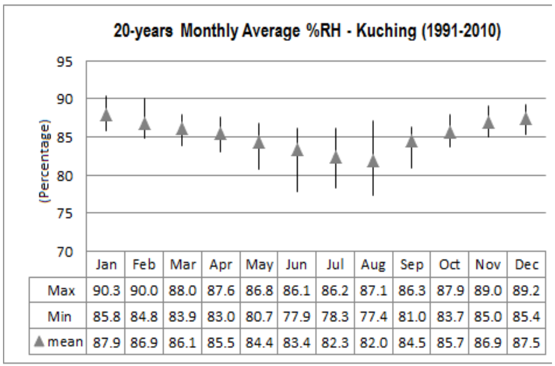
1.4.2 The Relative Humidity – Barrier to Dryer's Efficiency

Relative humidity (RH) is referred to the percentage of water content in the air at a given temperature and specific volume of air. The RH value in drying context imprints the ability to hold extra-evaporated H_2O; or in short, how thirsty the air is. Its relationship with the drying is always inversely related. The higher the RH value, the lower is the drying force.

Tropical rainforest climate usually fall short in its drying force due to high average RH values over the daylight and over the drying period. Figures 1.5a to 1.5c represent the RH data gathered from major pepper cultivation area. It is noticeable that the average RH is very high over the region. This causes a shorter optimum operating period as the heating energy will be wasted in heating up the surrounding and the dryer rather than efficiently applied to the end product placed in the drying chamber.

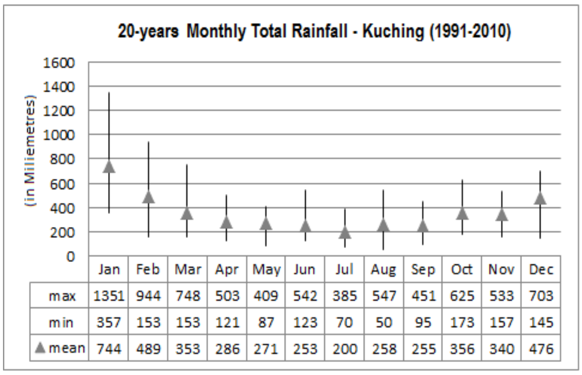
1.4.3 The Rain Fall – Barrier to Optimum Drying Environment

The rainfall values shown in the Figures 1.6a to 1.6c are the total rainfall information for the past 20 years ended 2010. It had expressed clearly how wet is the county where the main pepper product is produced. The amount of the rainfall decreases a little only in the few months in the 'dry' season (around May to September). In fact, in tropical rainforest environment, it is difficult to find consecutive completely-dry days in a week. In most occasions, a hot day with sudden flash will take place during the dry season and a moment of bright-sunny time in rainy days during the south-east monsoon period between Novembers to March (the wet season).



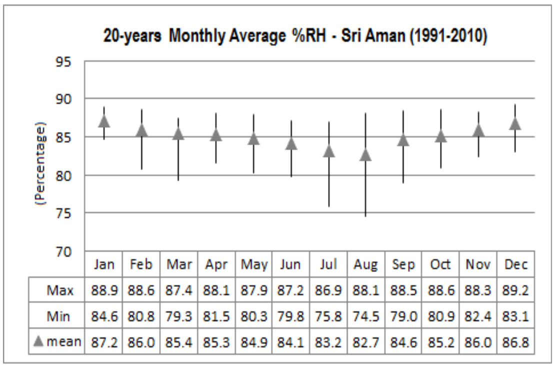
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max	90.3	90.0	88.0	87.6	86.8	86.1	86.2	87.1	86.3	87.9	89.0	89.2
Min	85.8	84.8	83.9	83.0	80.7	77.9	78.3	77.4	81.0	83.7	85.0	85.4
▲ mean	87.9	86.9	86.1	85.5	84.4	83.4	82.3	82.0	84.5	85.7	86.9	87.5

Figure 1.5a: 20-years monthly Average percentage Relative-Humidity in Kuching Area



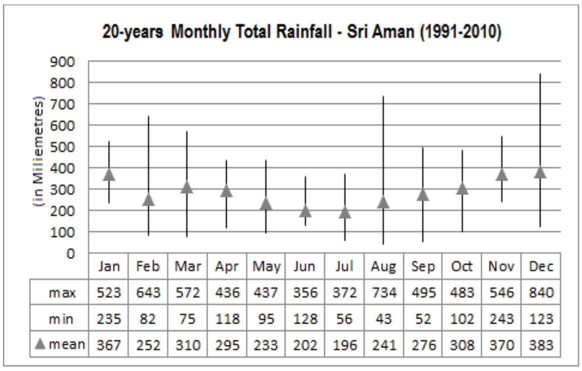
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
max	1351	944	748	503	409	542	385	547	451	625	533	703
min	357	153	153	121	87	123	70	50	95	173	157	145
▲ mean	744	489	353	286	271	253	200	258	255	356	340	476

Figure 1.6a: 20-years Monthly Total Rainfall (mm) in Kuching Area



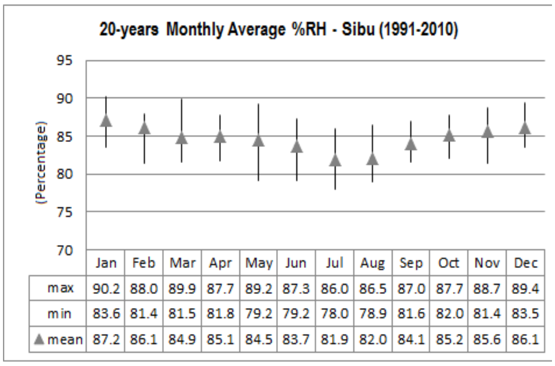
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max	88.9	88.6	87.4	88.1	87.9	87.2	86.9	88.1	88.5	88.6	88.3	89.2
Min	84.6	80.8	79.3	81.5	80.3	79.8	75.8	74.5	79.0	80.9	82.4	83.1
▲ mean	87.2	86.0	85.4	85.3	84.9	84.1	83.2	82.7	84.6	85.2	86.0	86.8

Figure 1.5b: 20-years monthly Average percentage Relative-Humidity in Sri Aman Area



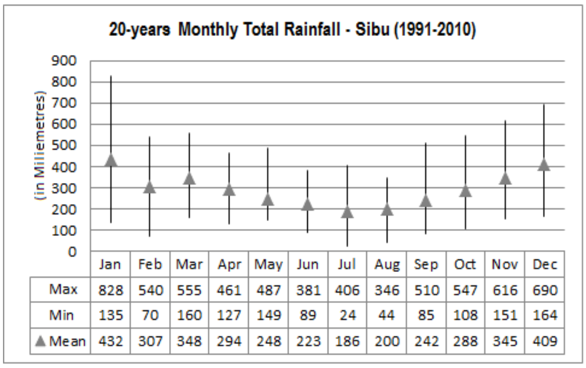
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
max	523	643	572	436	437	356	372	734	495	483	546	840
min	235	82	75	118	95	128	56	43	52	102	243	123
▲ mean	367	252	310	295	233	202	196	241	276	308	370	383

Figure 1.6b: 20-years Monthly Total Rainfall (mm) in Sri Aman Area



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
max	90.2	88.0	89.9	87.7	89.2	87.3	86.0	86.5	87.0	87.7	88.7	89.4
min	83.6	81.4	81.5	81.8	79.2	79.2	78.0	78.9	81.6	82.0	81.4	83.5
▲ mean	87.2	86.1	84.9	85.1	84.5	83.7	81.9	82.0	84.1	85.2	85.6	86.1

Figure 1.5c: 20-years monthly Average percentage Relative-Humidity in Sibu Area



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max	828	540	555	461	487	381	406	346	510	547	616	690
Min	135	70	160	127	149	89	24	44	85	108	151	164
▲ Mean	432	307	348	294	248	223	186	200	242	288	345	409

Figure 1.6c: 20-years Monthly Total Rainfall (mm) in Sibu Area

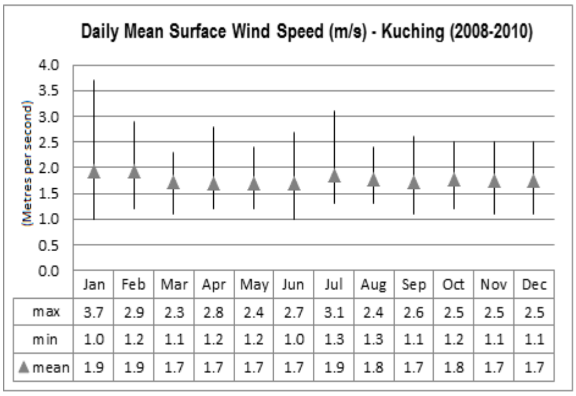
In this case, the conventional indirect solar dryer may not operate effectively as it captures insufficient heat source and the surrounding source air is considerably cold. Nonetheless, it can avoid the raw bits from being re-wetted since it is covered from direct rainfall.

1.4.4 The Wind – The Supplement

In the tropical climate near equator, breezes take place quite often. Figure 1.7 shows the daily mean surface wind speed which is favourable to use in the dryer design. Analysing this figure, we can see that average wind speed is between one and a half to two meters per second and this wind exists all the time throughout the year. Although the wind data was obtained at twelve meters above the surface at Kuching Meteorology Station, it also denotes indirectly the gentle breeze is expected from time to time at the ground surface.

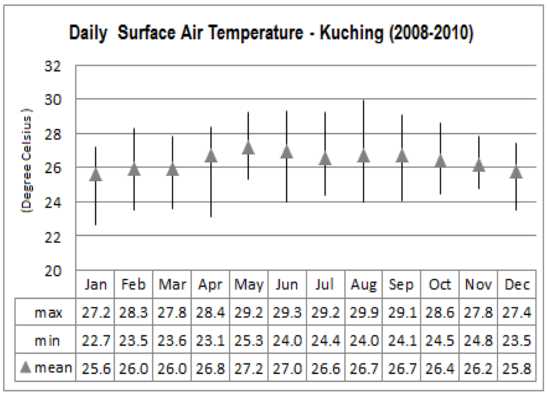
For optimum drying it is important to ensure that there is airflow presence on the surface of the raw product to encourage evaporation. In this case, it is referred to low-moist air or low RH air presences at immediate surrounding space of the pericarp of the pepper berries so that the water molecules will break-away from its surface tension. Wind blow encourages exchange of air and it helps to remove bound-saturated air in the boundary layer that enabling continuous drying processes.

Conventional solar dryers does not utilize this ‘breeze effect’ effectively, at very least, it has not widely and explicitly discussed in literatures until the recent few projects. This could be due to designers paying their attention mainly to the solar radiation. The utilization of the natural convective flow effect will, however, grant a surprise if one do embed it into the design.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
max	3.7	2.9	2.3	2.8	2.4	2.7	3.1	2.4	2.6	2.5	2.5	2.5
min	1.0	1.2	1.1	1.2	1.2	1.0	1.3	1.3	1.1	1.2	1.1	1.1
▲ mean	1.9	1.9	1.7	1.7	1.7	1.7	1.9	1.8	1.7	1.8	1.7	1.7

Figure 1.7: Daily Mean Surface Wind Speed (in m/s) for Kuching Area



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
max	27.2	28.3	27.8	28.4	29.2	29.3	29.2	29.9	29.1	28.6	27.8	27.4
min	22.7	23.5	23.6	23.1	25.3	24.0	24.4	24.0	24.1	24.5	24.8	23.5
▲ mean	25.6	26.0	26.0	26.8	27.2	27.0	26.6	26.7	26.7	26.4	26.2	25.8

Figure 1.8: Daily Mean Surface Air Temperature (in ^{o}C) for Kuching Area

1.4.5 General Discussion

In most of the natural sun drying exercised under the tropical climate, pepper berries can easily dried up to a certain moisture content in initial and constant-rate segment. After that, an extended long period of drying is needed to settle at the final stage. In general, massive water content is channelled out from the inner side of berries by capillary actions. It happens extensively during the constant-rate period. The surface evaporation is enhanced by presence of airflow as a result of the natural breeze or buoyancy. Drying happens pretty intensively at the early stage as moisture content inside of the raw berries is channelled out at higher rate and so does the surface evaporation. At the declining or final stage, once the channelling of the water content to the surface become harder due to decreasing moisture gradient, drying happens at a much slower rate. The condition gets worse particularly during a humid day which, it will take longer period of time before the peppercorn is ready for harvest.

Figure 1.8 illustrates the average daily surface air temperature in Kuching area between 2008 and 2010. The presented data shows that average mean temperature during the main harvest season is around 26ºC to 27ºC which is far lower than the optimum range from 45ºC to 55ºC for good quality peppercorn production.

The development of drying device that transforms the harvested raw food to ready use final product in countries in tropical region is an important task to minimise the post-harvest loss. It will practically save a fall between forty to eighty per cent due to very adverse conditions (Bukola & Olalusi, 2008). A study had reported that improper and untimely drying can lead to a substantial loss of agricultural products which should be stored for long term consumption (Bassey, 1989). Conventional passive solar dryers do not perform very well in the tropical rainforest region due to inconsistency of weather condition and very humid environment. Besides, it also requires large involvement of man power to loading and unloading the product during the rainy time. Therefore, in order to enhance the performance of the conventional solar dryer, some improvements that would lead to a shorter drying time should be done; for example, enlarging the collector area in an indirect solar dryer (Gregoire, 1984). Another option to intensify the drying power is to utilise an artificial device that employs forced convection, it will help to encourage surface evaporation.

1.5 The Problem Statement and Research Objectives

Today, conventional natural sun drying method is still carried out by smallholders in rural and sub-urban area as modern artificial drying facilities are too remote to reach. It is not that the farmers are not keen to produce better quality peppercorn in order to sell it at the better price, it is due to limitations on the knowledge and lack of investment will or capability. For most smallholdings, natural sun drying methods need no expensive tools and more importantly, with the quantity they produce, it brings very little difference to drive them to invest in a drying machine. Nonetheless, not many of them understand the advantages of using different technique for drying. So, they prefer the conventional way that they inherited from their ancestors.

There are a few issues related to the production of peppercorn in Malaysia: on the positive side, the weather condition is favouring the pepper cultivation. On the negative side, the same weather condition is bad for preserving by natural sun drying, especially during the main harvest season. It is necessary to study intensively to develop alternative options to provide pepper farmers with low cost yet effective solutions in peppercorn drying which, it will lead to production of high quality and better throughput especially in the situation of ever-changing weather condition.

1.5.1 Post-Harvest Processing and Storage Practices

In Malaysia, majority of the pepper berries are harvested during March-April (Zachariah, 2000). It is followed by post-harvest handling, which includes de-corning (threshing), blanching or washing and drying. For storing, the processed or raw peppers are usually packaged in gunny bags and kept under sheltered area (e.g. inside a room). Traditional peppercorn production requires some hard work and patience in addition to fighting the pepper plant diseases during the cultivating process. This has led to reduction of number of the farmers who are still happy to grow pepper vine especially after the downturn of pepper market a few years ago.

1.5.2 The Scope of Research

Pepper products can be used for different purposes: In the cosmetic industry, it is used to produce perfume; in the pharmaceutical industry it produces essential oil for medication; and in food industry, it is spices use as the food enhancer. The former two required modern advance-technologies to perform the extraction and further processes. These can only be done by bigger producers or companies. It is very unlikely the small farm can do it. In the case, farmers grow pepper as taste-enhancement product. Therefore the focus of this study will be black and white peppercorn productions by using a specially designed solar dryer.

1.5.3 Research Significance and Objectives

A dryer to be developed in this research can be simple and handy with satisfactory performance. It should be simple in operation, mobile, not requiring electrical or any other power supply and capable to perform drying at any weather conditions. The effectiveness of the dryer should depend on the normal conditions of environment at the dryer location.

The purpose of this study is to explore the possibility to develop a workable passive solar dryer system that will work well in tropical rainforest (climate conditions) area for local pepper smallholdings (small pepper producers). It is aimed to utilise existing technologies available in other fields and optimise for small quantity peppercorn production at lowest possible cost and sustainable.

1.6 The Report Overviews

This report is dividing into five chapters which describe analytical and experimental research performed in the research. Chapter one introduce the background of the Sarawak pepper, the production and its environmental conditions. Chapter two illustrates the existing pepper processing and drying technologies available to date. It also emphasizes the employment of existing workable solar drying technologies applicable in humid countries for agriculture use. Chapter three presents the description of the methodology used in this research. It details the studies done and techniques use to quantify the design. The chapter also describe the equipment and apparatus used in the research. Results and technical discussions on implementation of dryer are then presented in chapter four. Final chapter presents general discussion and conclusion cum recommendation for future work.

CHAPTER 2: LITERATURE REVIEW

This chapter looks into the literatures related to dryers. Primary attention is given to dryers that utilize natural resources to generate drying force. The focus on the review is to validate the employment of mixed-mode solar dryer in food drying under very humid environment. The content includes the classification and feature of various dryers, development and applications of different types of dryers, and the benefits of different drying technologies that can be utilized in raw pepper berries processing. The chapter also presents the studies done on existing technologies and ideas that need attention and to be implemented in the research.

2.1 The Myths of Drying in Food Preservation

Scientifically, Soteris A. Kalogirou (2009) refers drying as a "dual process of heat transfer to the product from heating source and mass transfer of moisture from the interior of the product to its surface and from the surface to the surrounding air". In human history, drying has been associated with food preservation for hundreds of years. It is sensibly explained by the raw foodstuff going through a process called dehydration, and it shrinks into smaller size and weights lighter so that the human community can stock up and consume it over a relatively longer period of time. Other than daily consumption, these dried foods are also traded for other means.

In reality, a product that went through the drying process is yielding a different result compared to the pure dehydration. In fact, dehydration is a process that only water content is eliminated from the raw product but not other substances. Dehydrated food will only change in size and weight but not in the colour and taste. Besides, it can be reinstated to its original condition once it is soaked in water. Whereas, the conventional drying process does not only extract the water content but also small amount of other substances like volatile oils which will vanished together with the moisture in the raw bits. Food which undergoes the drying process will never be able to restore to its original state as there is no way to restore those escaped chemical substance other than the H_2O.

Drying, however, is a convenient way of preserving food compare to pure dehydration. It requires less energy and simpler processes (refer to freeze drying section) in bringing the food to a state that it can be withheld long enough for later consumption. Drying also in some way offer variety of options to human society from a simple raw food bits in which, its end products may offer different taste and use. For example, fresh Piper Nigrum L. berries can be processed into black-pepper and white-pepper by processing its berries at different maturity state. The outcome delivers different aroma and spiciness taste.

2.2 Classification and Features of Drying Technologies Available For Food Preservation

There are various drying systems existed which are based on either conventional method, or modern technologies, or fusion of both. All of them have their very own characteristics and application advantages as well as limitations due to the construction features and environmental issues. They also have their unique cost and access to expert knowledge and technologies.

2.2.1 The Conventional Process of Drying

Conventional drying processes make use of the resources that exist sustainably in the natural environment. These resources are solar radiation, natural breeze, wood fire, et cetera. The utilisation of such resources has been continued until today in many places and in various combinations. Traditionally, sunray heating with the help of natural breeze is more popular than other sources like wood fire. It is because it requires less effort and the result is quite satisfactory.

Natural sun drying technique has been inherited for generations. People from different continents may have a little difference in application but the basis is the same – exposing the raw or semi-raw food bits directly under the sunrays. As radiation heating starts, the raw food bits will dry slowly until a very low percentage of water content is left. The food bit will then look shrink and darker in colour.

There are two main methods in arranging the raw bits: first, hanging the raw bits by string (or on a stick) and second, spread the raw bits flat in a container or directly on the hard ground. In the first method, one part of the raw bit is either being tied up with a string and suspend in the air; or it can also be hang onto a stick leaning against the wall or hanged with supports at two ends. This arrangement is usually suitable for fish and meat as well as bunches of fruit. The primary advantage of it is that the raw bits are exposing freely to the breeze while being heated up by solar radiation. However, its major disadvantage lies in the massive labour and space required to manage the drying activities.

The later arrangement involves spreading the raw food bits on a wide flat holder in order to keep the food bits exposed evenly to the sunlight. The holder can be the surface of flat rocks, wooden platforms, or mats. It can also be a simple container with wide flat opening. The mat and container can be made of bamboo slides, rattan, or in modern world, the PE or HDPE strips or metallic netting. The key application of this arrangement is meant for food bits of smaller size or those which cannot be hanged easily; like seed. Another advantage of this arrangement is that it is easy to work out and required less labour compare to the former method. Nonetheless, as there is only the topside of the food bits are facing the sun, the heating will be unbalanced if the bits are not turned over periodically. In his work on sun drying, Zachariah (2000) stated that if it is not managed properly, it would lead to poor uniformity in drying; the food bits may suffer microorganism contamination.

The main benefits of conventional method of drying are listed below:

- Sustainable drying force
- Simple construction and application
- Very low operation cost
- Requires almost ‘no’ literal support, practices inherited by custom
- Can be applicable to almost any type of food

However, it also comes with some inevitable disadvantages:

- Require comparatively large activity area
- May require massive manpower to look after the process
- Susceptible to unpredictable weather condition
- Susceptible to quality deterioration and loss due to contamination and artificial attacks

2.2.2 The Revolution of the Conventional Drying Practices – The Solar Dryers

Before the invention of modern food processor, the outcomes of traditional natural sun drying were greatly dependent on the climate at the geographical location. If the weather condition does turn unfavourable, farmers shall either have to scrap their harvest and suffer a great loss or to preserve their fresh harvest by other methods like smoking, curing (salting), or using artificial additives, et cetera. All these methods however will cause a great change in original taste though those methods might work. In the worst situation, it may not be perfectly safe to consume (due to additives). Therefore, in any case, drying may still be the preferable way of preserving most of the food.

For that purpose, solar dryer is developed. It utilizes solar radiation as the source of heating and practically concealed the raw food bits from direct re-wetting caused by direct exposure to raindrops. Besides, it also separates the contaminants and unwanted physical attacks from the surroundings (Esper & Mühlbauer, 1998). The primary benefit of using solar dryer over the conventional natural sun drying is the profile of the operating temperature. Since the drying process is practically taking place inside a box, the air exchange is theoretically limited by natural convection. Therefore, the operating temperature is usually much higher and stable. This, in some way, contributes to improved drying force presence around the raw bits. Conventional solar dryers are basically categorized into three main streams: direct, indirect, and mixed-mode; each has their unique characteristics in construction and operations.

2.2.2.1 Direct Solar Dryer

A direct solar dryer lets the raw bits exposed to the direct sunray similar to the conventional natural sun drying except there is a layer of transparent cover placed in between the tray and the light source. Solar dryer is usually constructed to channel the airflow in unidirectional path. In such a design, it has an inlet and an outlet airway to transport the moist-air to the surrounding air space by convection. Figure 2.1 shows the simplest type of direct solar dryer:

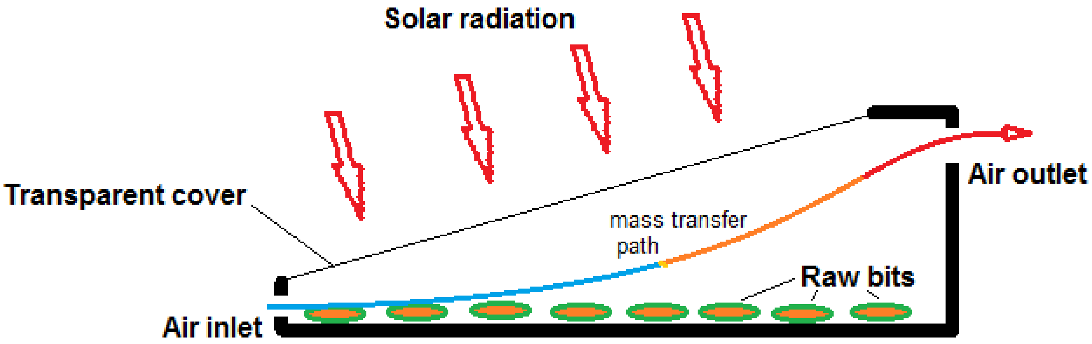


Figure 2.1: A Generic Direct Solar Dryer Layout and Its Operation Principle

The greatest benefit of a direct dryer is its simple construction and operation comparing to the other two. However, the downside is low efficiency in space-heating and uneven drying. The air temperature increases gradually as the air is flowing from the inlet to the outlet. This cause uniformity issue in drying as those bits located near the outlet will generally dried faster. In addition, raw bits have to be turned over periodically like what should be done in the natural sun drying; as only the top side of the raw bit is exposed to the sunlight. Direct dryer also has known issue on low per-unit-drying space since the food being dried must be exposed to the sunray directly.

2.2.2.2 Indirect Solar Dryer

An indirect solar dryer, on the other hand, does not let the raw bits be exposed to the sunray. In fact, it utilises the buoyant nature of the heated-air to complete the drying process. The raw bits are usually placed on a mesh or a plate with slotted-holes, and the hot air is coming from the bottom, which is sourced from the black-colour-painted solar collector. The hot air passes through the mesh, then the raw bits, and finally the hot moist air exited through the outlet vent located at the top corner of the dryer. The configuration is illustrated in Figure 2.2:

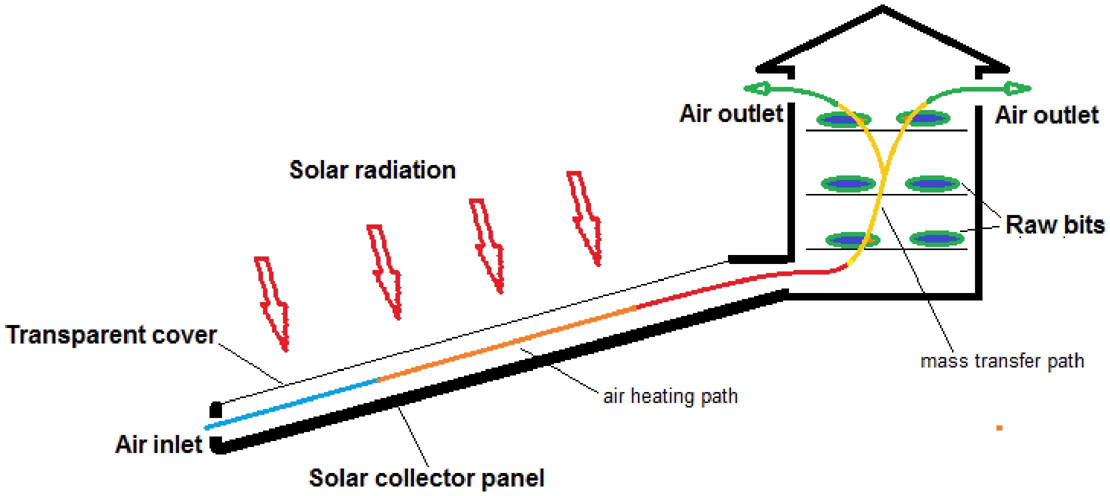


Figure 2.2: A Generic Indirect Solar Dryer Layout and Its Operation Principle

The key advantage of the indirect solar dryer over the direct configuration is that it can produce better drying force. Besides, the design enables expansion of raw bits holding capacity by vertical mean – multilayer arrangement. When the cool air passes through the sloped solar collector, the dark surface will result better air heating capability. When the air is about to leave the collector, it became very warm. The warm air will then passing through the mesh by natural convection and dries the raw bits before leaving the dryer.

Since the air is flowing upwards from the bottom of the raw bits, it promotes more uniform shrinkage as the flow path covers majority of the skin surface. This simplifies the operation as one does not need to flip over the bits from time to time. This type of device produces better drying force and results in a shorter drying period. Nonetheless, expansion of drying food layer too much in vertical direction may limit the efficiency of the dryer due to damper and cooler airflow after passing several trays. More often, the batch in the tray located down below will dry faster as it is exposed to greater drying force. In short, more layers will worsen the uniformity in dried bits over different layer of the same batch. The problem, however, can be practically minimized by rotating the trays top-down or bottom-up periodically to achieve more homogenous drying effect (Puiggali *et al.*, 1982).

Also, due to high operating resistance in the drying chamber caused by the multilayer trays configuration, the drying operation had reported been halted completely during the night and cloudy weather (Esper & Mühlbauer, 1998). The literature also stated its low acceptance in tropical region as it is comparatively expensive to build and there is no satisfactory results achieved during adverse weather condition. This will then increases the risk of facing a loss causing by the microorganism growth.

2.2.2.3 The Mixed-Mode Solar Dryer

A mixed-mode solar dryer has an idea of mixing both direct and indirect dryer into one. It inherited the uniqueness of both type of dryers. Figure 2.3 shows the simplest form of construction of a mixed-mode solar dryer:

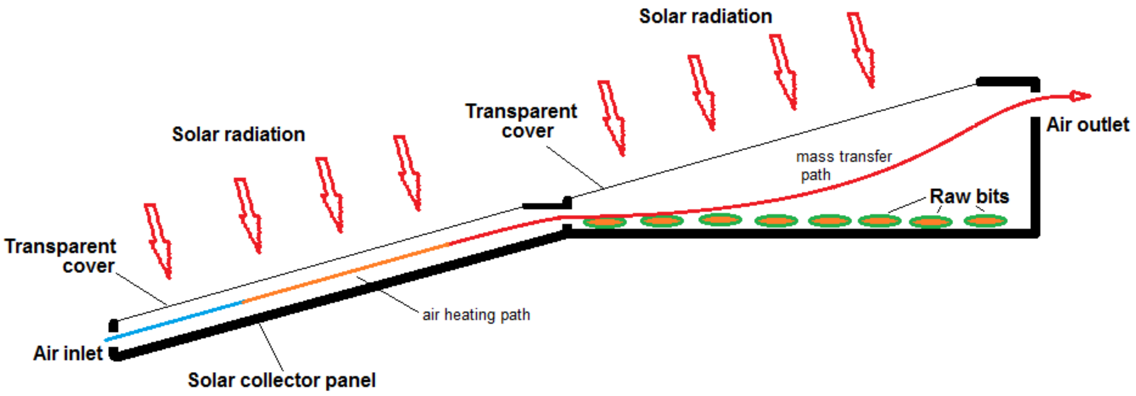


Figure 2.3: A Generic Mixed-mode Solar Dryer Layout and Its Operation Principle

The mixed-mode dryer can achieve a much shorter drying time. The design enhances the transportation of moist-air from the dryer to the surrounding by larger heat reservoir – both direct and indirect heating. The moist-air can at least maintain its temperature as it passes through the tray, and have enough buoyancy to float towards the outlet vent. The process encourages exchange of fresh air into the system. It however favours only for simple configuration of one to two layers of tray.

2.2.2.4 Brief Review on Conventional Solar Dryers

The dryer configuration discussed in this subsection is just conceptual examples. In actual practices, there are numerous branches of unique designs which, they are primarily developed to address differences due to the climate condition, site terrain, material and tools accessibility, knowledge and experience on particular drying object.

In the chapters of a handbook about solar dryers, Imre (2007) has introduced several types of dryers based on solar power. The study covers natural (conventional), semi-artificial and solar-assisted artificial dryers. The author classified a few solar dryers under the natural convective solar dryer as summarized in below:

- For natural convection direct dryers, a Cabinet dryer is one of the most primitive examples and it (direct dryer) has been introduced in subsection 2.2.2.1. The variation of it is the Tent-type dryer, which consist of a tall netting tray inside a triangular transparent cabinet. A bigger form of tent-type dryer is called Terrace dryer which has a structural framework to support higher capacity of raw bits. The 'house' is covered by transparent polyethylene sheet. The result should be considered quite satisfactory, as it has reported that 70% of coffee beans production in Colombia is depending on it.
- On the other hand, a Shelf-type and Static bed dryers are based on the indirect configuration where the hot air is channelled from the solar collector to the multi-layer perforated trays in the drying chamber used to dry the raw food bits. The author also stated that the drying process for these dryers can be further prolonged by adding heat storing and chimney which, it will yield another a 10% drying efficiency related to input solar energy.

2.2.3 The Revolution – Modern Technologies

The conventional practices do make sense in preserving food; however, they do not provide any good results during bad weather conditions. With recent growth in consumption of preserved food, especially spices like black pepper, it forces the production side to search for more promising systems to guarantee much higher quality and quantity in order to serve the market demand. As such, modern machines were invented to cater for the purpose.

Since the focus is on pepper drying, therefore only systems that could have the possibilities to be utilized for drying pepper product are discussed here.

2.2.3.1 Indirect Dryer

Indirect dryer is also called contact or conductive dryer. The uniqueness of such dryer is the separation of heating source from direct exposure of the bits being dried. The heat source can be the hot air produced from gas-burning, electric power heating, wood or coal firing, or other similar kind of heat sources. In between the heating source and raw bits, there is a secondary medium that acts as the heat exchange interface (Hall, 1980). Generally, indirect dryer is able to accommodate drying operations from a temperature of -40^oC to around 300^oC. In their chapter about indirect dryers, Devahastin and Mujumdar (2007) stated that when one incorporates the vacuum drying into the indirect dryer, it can be used to dry food because of lower temperature operations (due to low boiling point of the solvent – the H_2O). Besides, the hygiene factor leads by concealed environment, vacuum condition inside the dryer provides low oxygen content which will minimize or eliminate the oxidative reactions. This promises a better quality product. However, the main disadvantage of the indirect dryer is the limitation of contact surfaces. The flaw has made it less efficient in large-scale system.

2.2.3.2 Freeze Drying

Freeze-drying is a technique where the food is frozen before sublimation of water content took place inside the drying chamber. The process, as stated in the chapter about freeze-drying written by Liapis and Bruttini (2007), involves rapid-freezing and vacuum operation that results in a porous, non-shrunken structure in the dried bits. This structure enabled the dried bits to be rehydrated to its original state without losing its aroma and taste when water is added to it. Recent new product like dehydrated green pepper is done using this technique.

The freeze-drying is expensive at production but the cost can be compensating by easy handling and storage without the need of refrigeration as well as a longer shelf life.

2.2.3.3 Microwave and Dielectric Drying

Microwave and dielectric drying is referring to the heating mechanism inside the dryer which is powered by the mean of electromagnetic wave that vibrated at a specific range of frequencies. The radio wave emitted from the wave generator to the raw bits being dried and causes the molecule to vibrate and established a heat equivalent atomic motion inside the body and thus the drying process happened.

Microwave heating, unlike the conventional heat propagation, it encourages bulk heating and happens instantaneously and uniformly among the entire body of the bits. This technique has the advantage of controllable heating rate. In a handbook chapter on microwave and dielectric drying, Schiffmann (2007) did mention about recent microwave technology has the capability to control the heating with a rate of 1°C per century. This makes it possible to have a better controlled environment in drying various kind of food.

Microwave drying could achieve more efficient power consumption and selectable heating targets. It is also possible to reduce cost in flooring because of rapid drying capability. Nonetheless, the system has a well-known disadvantage on electromagnetic interference and human safety issues. Until now, there are researchers who are looking into this matter but none of them have been heard being successfully implemented the technique in peppercorn production.

2.2.3.3 Flash Drying

Flash dryer or pneumatic dryer is one from the direct dryer family. It is a continuous convective drying machine that utilizes either indirect or direct heating source. An example for indirect source is superheated stream and for direct source, it can be direct firing from oil or gas. Flash drying is suitable for drying granular product. Although its general working temperature is quite intense for food, with relatively short contact period due to the flash-flow nature the food bits will only experiencing relative low overall body temperature during the drying process. It is used primarily for surface moisture removal (surface drying after wash) for food bits that are heat-sensitive like peppercorn.

2.2.4 The Fusion Technologies

Modern technologies usually require substantial product quantity to achieve an economics of scale. It also requires enormous artificial power source and specialist support to guarantee smooth operation in the production floor. These, however, does not suit most of the players in the food industry. In short, not everyone can run a plantation due to huge initial investment and the subsequent running cost. Also, it might mean a waste if the market cannot consume that much of quantity at a given luxurious price.

In reality, some of the food industries exist by co-operative means where there are a lot of small stakeholders involved in the production and post-harvest processes. The product is then marketed through a facilitator who governed the quality and price. A perfect example for such formation is peppercorn production, marketing and distribution in Malaysia. There are numerous smallholdings spread around different areas across the land that keeps practicing their very own method of cultivation and post-harvest processes. At the end of the day, Pepper Board of Malaysia (MPB) is helping them to market their hard work to the entire country and export to overseas market.

Many individual smallholdings imply low production cost. When tied up with cultivation exercise in geographically wide-spread area, it will mean a small, low cost but efficient machine is needed for post-harvest process. In fact, not only in Malaysia, most developing countries are facing the same issues. Modern big machines can never fit the needs of those smallholdings who cultivate their crops far from the site of modern facilities. In fact, conventional dryers are more popular as it is affordable and easy to use despite, it may not provide satisfactory outcomes.

Countless studies were done for various food preservation using conventional solar dryers. Researchers are now interested in sustaining the traditional methods by blending the modern technologies and knowledge with a hope that it will overcome the existing known issues. As a matter of fact, many of them have successfully produced workable model for specific drying purpose.

2.2.4.1 The Economic Value of the Solar Dryer for Pepper Product Drying

As general rule of thumb, the economic value of a solar dryer is assessed from how much benefits it will provide compare to existing methods of practices. The assessment has to take into consideration of the throughput, operating cost, the initial build cost and relative opportunity cost as well as the service lifetime of the system. There are many type of solar dryer custom designed for a particular use under certain climate condition. Not all the solar dryers are able to provide high efficiency in food drying of all kind. Choosing the wrong dryer may result little in return or may have no value to the user at the worst case scenario. For example, a small direct solar dryer is installed to meet comparatively large amount of production.

In Malaysia, the major pepper cultivation area is in Sarawak state (Ravindran, 2000). Most of the pepper is harvested during March-April (Zachariah, 2000) in which, it is at the turning period from the end of Northeast monsoon to Southwest monsoon. The weather condition at this particular moment is wet with unpredictable rain pour. Using a solar dryer may yield better throughput at lowest possible initial and operating cost since it shields the raw pepper berries from the surrounding environment. The matter concerned here is which configuration provides the best return eventually under such climate.

2.2.4.2 The Semi-Artificial Solar Dryer

Imre (2007) defined the semi-artificial solar dryer as a solar dryer fitted with a simple ventilation system (with or without recirculation support) and a controllable vent to maximize the thermal efficiency; the example of this is the room dryer. The system utilizes force ventilation to enhance the drying force to resolve the flaw of the conventional solar dryer – slow mass transports issue.

Semi-Artificial Solar dryer has another advantage over the natural convective dryers – reduce the heat loss from the drying chamber. Conventional dryer will experience heat loss as the buoyant hot air flows toward the exit vent at the topside and cause a waste even it has not been utilized fully. In semi-artificial system, recirculation of under-utilized heated-air by simple small ventilation unit will help to promote better thermal efficiency inside the drying chamber.

The Room Dryers

A room dryer, like its name, is a dryer with relatively bigger space. It is frequently used in timber processing industry. The roof and certain direction of wall are made of transparent material to let the penetration of solar radiation for space and product heating. Usually an electric-powered fan is fit at the top of cooler side of the building near the inlet vent. It drives the air from the roof to the glazing wall and sucks back the buoyant but under-utilized hot air and again pushes to the heating region (similar to the semi-artificial solar dryer). A circular airflow generated by the ventilator will supply enough drying force to the wood product located at the middle of the room. From the lower vent at the collar ends of the room dryer, heavy moist-air will be led to escape. Similar configuration has been applied in grain drying. Air is forced through the grains from the bottom side of the grain room dryer. The advantage of the room dryer is that it can be designed to come with auxiliary energy source like gas-heated heat-exchanger which can be used during unfavourable weather condition (Imre, 2007).

The Hohenheim Tunnel Dryer

One particular advantage for the semi-artificial solar dryer is its low-power consumption for its artificial ventilator. It enables the use of tiny-scale power generation gadget to drive the ventilator, such as the photovoltaic (PV) cells. In fact, one of the famous low cost yet effective solar dryer is utilizing such configuration – the Hohenheim Tunnel Dryer. The dryer is first developed by Universität Hohenheim for smaller co-operatives for use in humid climate (Esper *et al.,* 1994). The dryer has a long and wide body; almost half of the area near to the air inlet is functioning as the solar collector and the remaining is the drying area. The UV-stabilized polythene translucent sheet is used as the covering wall along the dryer length. It is configured as a mixed-mode solar dryer but fitted with axial fans at the inlet vent. The outlet is kept opened to let moist heated-air to escape. The food tray is placed in the drying area with a little rise. Typical operation temperature of the dryer has fall between thirty and eighty centigrade with a volume flow rate of four to twelve hundreds cubic meter per minute.

The dryer operates by forcing the fresh air to pass through a long solar collector area before hitting the food tray across its top-side. Since the raw bits are spread in thin layer, a satisfactory result can be achieved easily. The dryer has proven work for many different food including meat, fish, crops and herbs. Since the power supply of the ventilation system for Hohenheim dryer is depending on the PV cells, the mass flow rate inside the dryer is than closely proportionate to the heating capability which, both are controlled by the amount of radiation reaching the dryer. This coincidence has contributed to the stability of thermal condition inside the dryer. Therefore, it offers better operating efficiency compared to other types of solar dryer under the same operating environment.

Another localized version of the Hohenheim Tunnel dryer called the AIT Solar Tunnel Dryer. It was developed by Asian Institute of Technology in Bangkok. It has a size-reduced body compared to the original Hohenheim dryer due to local land-holding capacities of most rural farmers in Thailand (Mastekbayeva *et al.*, 1998).

2.2.4.3 The Solar-Assisted Artificial Dryer

The main difference between the solar-assisted artificial dryer and semi-artificial solar dryer is that the former uses the artificial boiler, such as gas burner heat-exchanger, as the primary space heating source. The solar collector is just a secondary aid to reduce the standard operating cost. Whilst in the later system, solar radiation is the primary heating source. In term of complexity and cost, the solar-assisted artificial dryer is ranked top among all the solar dryers but it offers more reliable drying result as it is basically one of the small-scaled industrial direct dryers. It is almost independent from the negative effect from weather and surrounding condition.

2.3 Myths of Generic Pepper Processing in Malaysia

Pepper product in Malaysia is referred to the processed berries of the perennial climber called Piper Nigrum L. It was processed and distributed under different product varieties. It includes:

- Black pepper
- White pepper
- Dehydrated green pepper
- Green pepper sauces and pickles
- Pepper sweets, essential oil and perfume

Among all the major products, black pepper carries the most important weight in the product family. Around 80% of the raw berries are treated to form black pepper and it is followed by white pepper with an approximation close to 20%. The remaining goes to other product varieties.

2.3.1 Black Pepper

Black pepper is referring to the dried peppercorn made of matured, but not fully-ripped green berries. The green berries were dried continuously under the heat source until the moisture falls to approximately 10% to 12% region so that the mould growth can be effectively prevented. The raw berries can be dried directly or pre-treating it before the drying by going through a process called blanching to remove dirt and other foreign materials. The product that went through the blanching produces more shining and uniform but darker in colour berries. The blanching process is done by soaking the raw green berries in hot water for minutes before it is been dried. Nonetheless, due to the labouring and relative cost consideration, the process might not seem to be practical (Chih and Sim, 1977).

Green berries can be separated from its fruit spikes through threshing process. Conventional method is trampling the pepper stalk over a half-inch-square wire mesh fitted on a wooden tray. In olden days, some cultivators will perform the separation process on the flat bed made of wood or on a mat and the process happens only after the drying process.

Figure 2.4: Typical Pepper Berries Used for Peppercorn Production; Left most: matured green berries for black peppercorn; Second from the left: partially ripe, use to produce black (traditional) and white (recent days) peppercorn; Two pictures on the right: ripped pepper berries for white peppercorn production.

Once the berries were threshed from its spikes, they are spread in thin layer on a wide flat area to be dried under the sun (conventional natural sun drying). It usually takes around three to four days to complete the drying process if the weather condition is fine and sunny. In general, harvested green berries can be stored up to a maximum of eleven days. However, the process is recommended to be done within three days to guarantee darker appearance and uniformity in colour.

2.3.2 White Pepper

White pepper requires a little more complicated processes before the drying exercise. Fully ripped green berries is harvested and held in the gunny sacks. The sacks is then left retting in a pond or running stream until the pericarp of the berries are rotten. It is later being trampled and washed in a basket to remove the rotten pericarp and pepper stalks. The soaking process will usually take around eight to twelve days in stagnant water or ten to fourteen days in running stream (Chih and Sim, 1977). It is also reported that the white peppercorn produced by soaking raw pepper in the stagnant water will look dull or brownish; whereas, cleaner and brighter and white appearance can be achieved if the process is carried out in running water. The report also stress that it is crucial for raw pepper berries to be processed (soaking in the water) in less than five days to guarantee good colouring.

Drying of raw berries for white pepper required more careful consideration on the weather condition. Since the de-capped berries are more prone to mould attacks, it is crucial for berries to be dried quickly. If the weather is hostile, the soaking process can be prolonged to a maximum period of twenty-six days. The extension will only seem to cause a minor breakdown of seed coat but no deterioration in overall quality. If natural sun drying is to be adopted, it also recommends the raw berries should be flipped over periodically to prevent mould growth during the drying process. At the end of the process, the final peppercorn should have a moisture content of less than 12%.

2.4 The Component of a Generic Solar Dryer

A. Mujumdar (2007) in his chapter about drying principles stated that in a typical thermal drying operation of a wet solid, there are two processes that will occur concurrently: first, external evaporation of surface liquid and, second the transportation of internal moisture to the surface. Generally, most of the dryers supply the heat through conduction, convection and radiation; either in combination of all heating arrangements or just some of them. In the drying process, the surface of a wet solid is first being heated up and the heat penetrates slowly into the body of the solid. Slowly, the surface of the solid will become dry and it encourages the internal channelling of water and other matters out to the surface before further evaporation take place. The channelling process can be by diffusion, capillary flow or even pressure or moisture concentration gradient initiated by internal pressure set up due to the shrinkage of solid body.

Inside a solar dryer, exposure of the food bits directly to the sun radiation will cause a direct heating of the raw bits besides warming up the space in the drying chamber. When the radiation heats up the pericarp surface, the evaporation occurred at the outermost thin water film and cooling down the surface of the individual raw bit. At the same instant, the heated-air around the raw bits will further boost the evaporation.

The evaporation process happened when the water molecules on the surface of the wet solid received enough kinetic energy, it breaks away from the surface of the H_2O crowd and get suspended in the air. When this occurs, the water content in the wet solid is forced to propagate to the surface in order to maintain the freshness of the pericarp. This happens until an equilibrium state occurred, assuming the surrounding air is not moving at a given temperature. Therefore, to guarantee a continuing drying process, saturated air has to be withdrawn from the surface of the skin.

2.4.1 The Solar Collector

In evaporation process, the presence of warm air is vital to enhance the drying rate. The warm air at elevated temperature will result in lower relative humidity and offer higher moisture holding capacity. This is technically referred as better drying force. Since a solar dryer is in a partially enclosed container, the heat source can be obtained from both convection and conduction besides the direct radiation. As the raw bits in most solar dryers are suspended on a mesh or equivalent, conduction heat transfer may become rather insignificant compare to convective heating. In fact, for indirect and mixed-mode solar dryers, solar collector is used to produce hot air in order to ensure a continuous evaporation inside the drying chamber.

A solar collector in the solar dryer context is referred to as an air space that produces the hot air through the convection process. The solar collector in agricultural drying is usually one of the flat-plate collectors (FPCs) in a long tunnel setup with its top side covered with a transparent or translucent material. The inner bottom surface is typically painted in black colour or padded with radiation absorber like charcoal, rocks, water packs, et cetera. It has two openings at both ends: one end is for intake of fresh cool air and the other is supplying the hot air to the drying chamber. The advantage of this type of collector is cheap and much simple to produce. In addition, it collects both direct and diffuse radiation in stationary position.

When the absorber plane is tilted and facing the sun, it will turn hot and thus heats up the air appearing near to its surface. The heated air is then propagated towards physically elevated end; which it is then channelled to the dryer chamber. Generally, the longer the collector, the hotter the output as the heat is accumulated along the collector length.

There is no perfect collector. The efficiency of a collector is dependent on the density of the radiation flux hitting the absorber plate and the energy gained by the working fluid as shown in equation (1) (Kalogirou, 2009):

$$\eta_{\text{collector}} = \frac{\dot{m} c_p (T_o - T_i)}{A_a G_t} \tag{1}$$

$\dot{m}$ = Fluid flow rate

C_p = Specific heat capacity of working fluid

T_o = Outlet temperature

T_i = Inlet temperature

A_a = Gross collector aperture area

G_t = Global solar irradiance at the collector plane

2.4.1.1 The Effect on Physical Arrangement in Actual Application – The Tilt Angle

The tilt angle of the flat-plate collectors (FPCs) usually determines a lot in its efficiencies. In book chapter written by Soteris A. Kalogirou (2009) stated that the best slope (tilt angle) for the FPC is equals to the latitude of the physical location. Still, the arrangement can be varied by 10^o to 15^o depending on applications in which, for space heating purpose (solar collector), a latitude plus 10^o is recommended for optimum solar radiation exposure during the summertime and a minus to the same degree during the winter (Okujagu, 1989). The statement has nearly coincided with the studies done by Sulaiman *et al.* (2005) in their solar electricity generation works. They stated that 15^o tilt from the horizontal is the best for Malaysia application as the geographical boundary of this country is below 5^oN latitude.

2.4.1.2 The Collector Absorber Plate

Absorber in the context of a solar dryer is an object or surface, usually with wide surface area, that is meant to transform the sunlight to heating energy and resulted corresponding space heating. The absorber can be in form of flat, corrugated, or grooved plates. To achieve better efficiency, an absorber plate usually will be coated with a layer of high absorptance and low emittance material, which is called selective surface. For low cost solution, matte black paint is used. Although it is not applicable to high performance solar systems, it is good enough for use in general agriculture drying application with the heating requirement below forty centigrade and above the ambient temperature (Kalogirou, 2009).

2.4.1.3 The Glazing

The cover at the top side of a solar collector should be made of a radiation-transmittable material so that it will allow the space and the absorber below it to be heated up and produce hot air. Selection of the glazing material for space heating purpose in outdoor application must meet at least three criteria: first, high transmittance for near-infrared component while low transmittance for far-infrared component; second, have low emittance property; and finally, have good impact property and easy to maintain. These requirements are important as the glazing layer is basically acts as the isolation layer (avoid convection losses) and primary energy source transmitting window in a solar dryer. Any deficit in those requirements will reduce the true performance of a solar dryer; as it causes an underutilization of the available energy from nature.

To achieve an optimum solar gain or passive heat gain, the transmittance property of the glazing material is crucial as it determines optimal radiation penetration before it finally reaches the absorber. For heating purpose, the main sunray component is infrared; to be exact, the long-wavelength far-infrared component. A good glazing should be transparent to short-wavelength near-infrared radiation and opaque to long-wavelength far-infrared thermal radiation emitted by absorber (Kalogirou, 2009).

Other than the performance and protection, the glazing should also possess other properties to ensure ease of use and maintenance. Generally, the glazing should possess good impact property and UV stability to guarantee its long service ability. It should also be easy to clean so that the dryer will operate at its optimum condition at all time.

2.4.2 The Heat Storage

The aim of implementing the heat storage in a solar dryer is for keeping excess energy during the daylight in order to assist the drying operation at night (Imre, 2007). The benefit also extended to overcast days. The operation makes use of thermal storage medium as heat reservoir to absorb and accumulate the energy when the surrounding temperature is higher, which is to be use during the absent of heating source.

There are pros and cons of utilizing heat storage. First is to deal with the heat capacity of a collector and the amount of the storage material. In general, the more storage material use, the longer a dryer can maintain its working temperature. However, excessive storage will cause a drop in normal operating temperature. The condition will be worst if the weather condition is poor. Furthermore, heat storage also contributes to overall weight and cost of the dryer. Besides, the use of heat storage will cause a slow start up however it offers more consistent drying force as it normalizes minor fluctuation in the collector when the air passes through the heat storage region.

2.4.3 The Drying Chamber

The drying chamber is the box containing the raw bits to be dried. For direct and mixed-mode solar dryer, it is just a part of the collector. Whereas, for indirect solar dryer, it is a separate compartment where the hot air meets the raw bits and causes primary mass transport to take place. Basically, it consists of a column with trays inside it where the hot air from the inlet or the collector penetrates through the tray and exhausts to the outlet.

2.4.4 The Inlet and Outlet

A conventional solar dryer favours mass transportation. The operation starts from cool air intake from an opening and hot and humid air exhaust through the exit vent or outlet by natural or forced convection. Conventional passive solar dryer design usually has its inlet and outlet unnoticeable as it has little emphasize. The operation is dependent on the convection operation inside the collector and drying chamber. Recent research done on force convection technique and some passive dryer utilises a solar chimney has gradually awakes the researchers on the need to deal with such issue in order to improve the effectiveness of the solar dryers.

2.5 Utilization of Solar Updraft in a Mixed-mode Solar Dryer

All natural-convection solar dryers utilize the buoyancy of the heated-air to induce the mass transport; yet, the drying process is slow. It is because the air exchange is dependent on its operating temperature – the higher it is the better in efficiency. This is the main reason why force convection system is introduced to the solar dryers in the first place. However, artificial force convection system may not be applicable to places where artificial power supply is limited. Same issue may happen to solar-powered system (through photovoltaic cells, PV) for sites that received limited amount of sunshine.

In addition, another important component in conventional drying is the thermal condition inside the drying chamber. Unless a supplementary artificial heating system is used to support the force convection system, a drop in temperature will mean a deficit in drying capability. How to maintain a balance between the mass flow of the moist-air and temperature level inside the dryer has become the challenge in solar dryer design.

2.5.1 Introduction

Solar updraft system is a kind of solar chimney system originally designed for electric power generation plant (Schlaich *at el.,* 2005). It is a thermal system, which consists of a round-shape solar collector with a centrally-placed updraft tube to induce the convective flow, which drives turbines at the entrance of the chimney to generate electricity. The operation of the system is simple; the air molecule is energized by solar radiation in the collector arranged in mild upward slope towards the updraft tower – the chimney. The hot buoyant air travels along the bottom of the collector to the bottom inlet of the updraft tower by natural convective flow. The crowding of heated-air at the bottom of the chimney creates a pressure difference between the bottom inlet and the top outlet and causes an air-draft along the chimney, which further drives the air in the collector to the surrounding atmosphere. The report has drawn the conclusion that the updraft velocity of the air is closely proportionate to the product of changes in collector temperature and the height of the chimney.

2.5.2 The Possibility of Utilization A Long Chimney in Agriculture Dryer

Conventional solar dryer utilizes very short chimney to expel the moist-air from its drying chamber. Such chimney does not help much other than to provide a guided airway and as a shield and separator. Long chimney may have positive outcome if it is to be applied to a solar dryer to replace the existing solar dryer solutions. By a new use of existing technologies, Schlaich *et al.* (2005) has formulated the free convection flow for the updraft system. It is expressed in below:

$$V_{\text{tower (max)}} = \sqrt{2 \cdot g \cdot H_{\text{tower}} \cdot \frac{\Delta T}{T_o}} \qquad (2)$$

And the efficiency is expressed by (Schlaich, 1995):

$$\eta_{\text{tower}} = \frac{g \cdot h}{c_p \cdot T_o} \qquad (3)$$

g = gravity

h, H_{tower} = height of the chimney

ΔT = Temperature difference between the inlet and outlet of the chimney

T_o = Surrounding temperature

C_p = Specific heat capacity of working fluid

From equation (2), a maximum free-flow current can be achieved by increasing either the height of the tower or the temperature difference between the top and bottom of the chimney (updraft tower). This makes sense for such system to be applicable to a solar dryer. In fact, Ferreira *et al.* (2008) did a technical feasibility study on food drying utilizing solar tower. In their studies, a prototype was built in Brazil and tested by drying coffee grains, banana, and tomatoes. The result concluded that the system is feasible to be utilized in food drying. However, there are some issues to be considered: first, the cost of the huge tower is quite significant and second, the food to be dried has to be placed near to the chimney inlet, and multilayer-tray arrangement should be avoided. Apart from that, the authors also suggested that a layer of thermal insulation should be implemented above the ground to maximize the thermal efficiency in the collector of the system.

2.6 Related Literatures

Solar chimney has two very distinct perspectives. The first one expresses clearly that the chimney appeared to assist in air updraft as the chimney itself only absorbs minimal solar energy (the chimney does not need to appear in dark colour). The primary updraft source is coming from buoyancy of air due to the hot air formed in the collector and appears at the entrance to the vertical chimney. The air-draft is very much dependent on the pressure difference between the lower entrance and upper exit of the chimney. This type of solar chimney usually does not emphasize much on solar absorptance and external insulation. On the other hand, another configuration details the chimney itself as the primary tool that causes the air updraft as the chimney is absorbing the solar energy and energizes the air inside the column (the chimney body is painted in dark colour). This particular chimney does quantifies very much on its selective surface and how good is the insulation around the chimney body. Technically, the said chimney is a solar collector. Jörg Schlaich (1995) and Ferreira et al. (2008) have illustrated one typical example for the first perspective and Afonso & Oliveira (2000) and Ong & Chow (2003) presented the other.

There are some literature sources emphasizing on certain ideas. The following sections are digesting of those.

2.6.1 Afonso & Oliveira (2000)

There are not many research papers emphasising on the wind effect to a solar-based system. Afonso and Oliveira have their simulation and experiment studies to prove that the wind effect to the chimney can never be neglected. In their study, it is proven there will be a general increase in airflow passes in the chimney column with the presence of wind at the upper exit of the chimney. They stated that "…They are more significant for ventilation flow rate, in some days, which may be due to changes in wind pressure coefficient, which is not constant, as supposed in the model…" and "Due to the variable (almost random) nature of wind, the design of a solar chimney can be done without considering the wind effect, which will underestimate the real ventilation rates". From here, it is clear that one may consider utilizing wind effect if the nature of the climate at a locale does supports.

Solar dryer and solar assisted thermal comfort of a house has one similarity; both encourage exchange of air between the internal compartments with outside atmosphere through space heating model. Although the emphasis is different and their method may be dissimilar, the effect is the same. From the simulation and experiment done on the use of solar chimney in enhancing the airflow in a building (compartment), the literature stressed that a solar chimney is proven to have a significant positive effect in increasing flow of air in the building. They also discovered that the thickness of the absorber (in the case, the chimney made of ceramic material) does affect the rate of airflow – The thicker it is, the slower it is; yet it does extend the service further to night time. The great effect, however, needs to be maintained by effective insulation at the external side of the chimney. From their study, there is a 60% drop in efficiency if it is not insulated properly.

Apart from that, their experiment studies also demonstrated the significance of the chimney height and width in overall airflow rate. Their studies conclude that the increase in height and width of the chimney will enhance the airflow rate. However, widen the width of the chimney seems obtaining better effect than the height. The studies discovered the airflow rate increase linearly with the chimney width while smaller effect obtained as the height increases. Yet, the system efficiency will respond positively to chimney height rather than width.

2.6.2 Ferreira *et al.* (2008)

Ferreira *et al.* had built and tested a food dryer in Brazil that utilizes a solar chimney. Their purpose was to investigate the feasibility of a dryer utilizing the solar chimney. The dryer is of circular plan with a vertical cylindrical tower placed in the centre of the drying area. The dryer is covered by translucent plastic thermo-diffusor film at an elevation of half-meter above the ground. The chimney is made of wood sheets and fiberglass. The air inlet of the dryer is at its opening at lower end of the outer perimeter of the drying area. The air exits at the upper end of the solar chimney which is twelve point three meters above the drying area. The dryer covers an area of twenty-five meters in diameter in circular shape.

The characteristic study of the solar chimney for agriculture application was done by investigation of the ambient conditions and the thermal profiles of the airflow inside the prototype. In their experiments, pyranometers were used to measure the incident solar radiation; psychrometers were used to measure the relative humidity of the working air; k-type thermocouples were used to read the temperature parameters; propeller based anemometers were used in collection of airflow data; and finally an analogical scale was used to obtain the mass of the food in their experiments.

The experimental study was done on three types of food namely: coffee grains, whole bananas, and tomatoes. Every test of either sample was separated into three sets; one set was used to find out the initial moisture content, another set was dried by natural sun drying, and the remaining set was sent to dry inside the dryer. The experiment divided the samples into nine groups for statistical treatment, as the experiment is unrepeatable due to random nature of the environmental parameters.

From experiments done over ten months in 2003, they witnessed an increase in internal airflow temperature by a maximum yearly average of 27ºC ± 1ºC and a drop of around nine per cent in relative humidity over the ambient condition. They have concluded that solar chimney did really work for food drying.

The findings, however, exposed the weaknesses of the dryer of the kind. One of them is the uniformity of the distribution of airflow along the flow path towards to the centre of the dryer at where the chimney is located. The air flow slower at the outside perimeter and faster as it goes nearer to the centre. The presence of massive drying force only appears around the centre region causing uneven drying rate among different samples distributed across the entire drying area. Besides, significant heat loss occurred due to the exposure of the ground inside the dryer, which does not contribute effectively as expected during night time. In the case, there is a need for a thermal insulation layer at the bottom of the dryer. Finally, they discovered the plastic cover used in the dryer did not offer positive help in space heating. Their findings had highlighted the importance of the use of glazing with high transmittance to sunray and vice versa to infrared radiation in order to achieve optimum operational conditions in a solar dryer.

2.6.3 Alghoul *et al.* (2005)

Alghoul *et al.* had done a review on materials applicable for solar collector used in solar water harvest system. Their paper discussed some issues, which will be beneficial to the design of the proposed solar dryer. From the glazing perspective, they recommended low-iron glass as it has high transmission and low reflection of sunray that they believe will help in collector efficiency. They also stress that most plastic glazing are much cheaper and lightweight but have reduced performance, shorter service lifetime due to rapid deterioration under extreme service condition, and risky in relation to fire safety. However, some polymeric materials have slowly gained attention as they offer significant cost saving and appeared to be stable to heat and UV radiation.

Their recommends the materials choice and construction of dryers must be characterized under “weather resistant, fireproof, durable, dimensionally stable, and strong”. They also commented the dryer under construction should be “completely and permanently sealed against moisture intrusion.”

2.6.4 Joy *et al.* (2002)

Joy *et al.* had a review on the German's Hohenheim dryer on pepper (Piper Nigrum L.) drying. The experiment was carried out in Kerala, southern India from January to March 1999. Total three batches of fresh samples of sixty kilogram each were collected from three different areas and tested in Botany Research Centre of Sacred Heart College near Kochi, India.

The dryer used for drying test have a 7x2m^2 collector area and 10x2m^2 drying area. The experiment was done with single layer spread of blanched berries on the mesh tray that is placed two centimetres above the drying area. Two small solar-powered axial fans supply the required airflow over eight-continuous-hour experiments starting at nine in the morning on the test days. After the recovery, random samples of dried product were sent for physic-chemical quality analyses. The research team also obtained those commercially available conventionally dried pepper samples to benchmark their experimental results.

The experiment had shown a green light for pepper drying in tunnel structured forced convection dryer. During the experimental study, in the dryer it was recorded a maximum operating temperature of 70ºC and it led to results showing a reduction of drying time from five to seven days to merely eight hours sunshine. It was also recorded a final moisture content of 12.4% and the dried product was compared to 12.4% to 14.4% moisture content product achieved by commercial product based on conventional drying method. The study had shown that the product dried by tunnel dryer has higher physic-chemical qualities over the products produced using natural sun drying. This confirmed the importance of post-harvest technology in improving pepper quality.

2.6.5 Gregoire (1984)

Gregoire discussed how to choose a suitable solar dryer for food drying in his technical paper. In the paper, the author stated, "as drying proceeds, the actual amount of moisture evaporated per unit of time decreases". The statement was further explained as the pure evaporation happens at the surface in phase-one (*initial-period*), followed by, in phase-two (*constant- and falling-period*), the penetration of moisture from inner body to the surface and evaporated to the surrounding airspace. The paper also stresses the potential of overheating caused by slower rate of evaporation may result case-hardening to occur, and this will trap moisture inside the product. The suggested solution was either to increase the airflow across the drying bulk of the product or to reduce the heat collection.

The paper had recommended that one should blacken the inner side of the dryer to improve dryer efficiency. Besides, the tray mesh used to hold the product should be the coarsest possible in order to encourage airflow at low resistance. This will promote better moisture evaporation from the product. Other than that, a solar chimney can be implemented to encourage better airflow.

For the choice of material, the paper stated that rigid plastic glazing has similar transmission as glass while it is durable against breakage and may sustain about ten years in service. On the other hand, thin plastics film is cheaper with good transmissivity yet it can be punctured and torn easily as well as it may degrade quickly.

2.6.6 Ezekoye & Enebe (2006)

Ezekoye and Enebe had studied a portable passive solar dryer custom built in Nigeria. It is aimed for use in period with low temperature and high humidity. The dryer is constructed using angle iron as the frame structure and Perspex glass as the glazing at the topside and two opposite sides. The bottom and remaining two sides (not facing the direct sunray) are covered by plywood. There are holes at the bottom plywood plate, which act as the cool air inlets. The top glazing appeared in slopes with the upper edge covering an exit vent located at the topside of one of the plywood wall. The dryer make room for air intake by twenty centimetres elevation from the ground.

The dryer has two trays arranged in vertical cascading structure. The upper tray will receive most radiation as it is exposed directly to the sunray compared to the lower tray. From their experiment, lower tray can achieve an eight to eighteen centigrade difference in temperature from the ambient while the upper tray records a difference of nine and a half to twenty-six centigrade. From the drying curves showing the moisture loss over days for upper and lower trays and natural sun drying, both curves for the trays placed inside the dryer shown a positive increment at a slightly different rate while there is a sudden slump shown in the curve utilizes natural sun drying method. This shows the possibility of re-wetting as the crop is absorbing moistures from the surrounding.

The literature concludes that there is a prospect in overnight retention of crops in the dryer as re-wetting is not possible since the dryer is sealed from dew and rain.

2.7 Discussion

All different types of dryers do have their very own benefits and drawbacks under specific environmental conditions. As the application criteria is to meet the requirement of the local climate and expectation of the local farmer, many of them may be impractical due to the cost and operation complexities as well as effectiveness of the dryers under the tropical rainforest climate. As we can see from the review, the only one that may meet the criteria is the mixed-mode solar dryer.

This research does not have any intention to alter the existing general practices nor the processes of conventional peppercorn production apart from the drying part. The dryer design is aiming for easier implementation with greater recoveries. Of course, the goal is to offer a balance between the throughput and overall quality without, ideally, affect existing work-style of the local end-user.

CHAPTER 3: METHODOLOGY

This chapter introduces to the reader the design consideration and implementation of the dryer under the local climate (tropical rainforest). The study also presents the operation description and test procedures to validate the usability of the model.

3.1 System Requirement and Implementation Analysis

Soteris A. Kalogirou (2009) in his book called Solar Energy Engineering has addressed that "*The objective of a dryer is to supply the product with more heat than is available under ambient conditions, increasing sufficiently the vapour pressure of the moisture held within the crop, thus enhancing moisture migration from the within the crop and decreasing significantly the relative humidity of the drying air, hence increasing its moisture-carrying capability and ensuring a sufficiently low equilibrium moisture content*".

The statement reflects the basis of the targeted environment achievable inside the drying chamber so that the described operation will happen unobstructed. Therefore, the primary idea to the design consideration is the understanding of the surrounding condition of the work cell; this will take into account of all the climatic parameters. Furthermore, since the design is to be optimised for certain usage at specific needs, other parameters like the land terrain, size and holding capacity et cetera should be accounted for.

3.1.1 The Issues for the Practical Work cell

There are some factors needing special attention as summarised from the literature studied in order to design a more promising solar dryer for local use. They are presented in below.

3.1.1.1 The Effect of Atmospheric Factors

The Tropical climate exhibits uneven distribution of radiation at all time (Ong and Chow, 2003). This has become one of the constraints limiting the drying practices in Sarawak, which is believed to be influenced by heavy cloud cover. It is hard to keep a stable temperature inside a dryer as instantaneous heating source is unstable over a day. The situation is getting worse with unpredictable rainfall that cools down the surrounding atmosphere. This will cause an adverse effect inside the drying chamber as the air exchange happens, ideally, all the time between a dryer and its surroundings.

Apart from that, high relative humidity will further depreciate the heating capability as water molecule is considerably good in heat absorption. This will cause a longer start up time after dawn as well as temperature recovery from the wind effect or a flush. Moreover, it is also harder to achieve optimum drying temperature inside the drying chamber since the air exchange exists by nature. The wind effect, however, can be used to promote the airflow which will favour mass exchange inside the drying chamber.

3.1.1.2 The Terrain and Usage Practice

Portability and adjustability enables flexible selection of the best location or angle for optimum solar gain. For small scale drying operation, the dryer is usually presence in small size. A portable dryer allows user to move around at the site freely for ease of operation and storage. For example, one may want to collect the finished product from the dryer while it is still raining. Portability allows one to easily move the dryer to a covered area and unload the product without the risk of being re-wetted. Besides, the rural terrain is usually uneven. A portable device may experience incorrect tilting for the best solar gain if the dryer is not tuneable. These incidences are quite common in local practices.

3.1.2 The Characteristics of the Dryer

There are some primary concerns about how a research will bring a change to the existing practice. The dryer must have an overall benefit over the conventional method in order to attract the potential users to abandon their traditional practices and go for it. In the case, how realistic is the new idea in accommodating their daily needs as well as ease of use is the key to the acceptance.

3.1.2.1 Optimum Heat-flow Consideration

Uniformity in drying is crucial to ensure near-identical product quality. To achieve this, consistent drying force is expected to be present at all points on the drying bed over the entire drying period. It is quite impossible for a generic passive solar system to achieve that condition. It is even more difficult to realize as the size gets bigger. However, one can minimize the variation by balancing the convective flows inside the drying chamber.

From the literatures, the drying force during the daylight is determined by the heat flux absorbed and the moisture absorption capability of the air presence at the boundary layer of the pepper berries at its pericarp. In the case, the most effective way of realising equal heat flux distribution is to let the berries expose directly to the sunlight. The solid (pepper berries) will absorb heat from the radiation for internal water pumping; it will also contribute to the air heating within the boundary layer at the pericarp surface in which, it encourages vertical convective flow.

In addition, secondary warm air supply is needed to enhance the drying force before the fresh air hits the berries. Since hot air is buoyant by nature, it should not be supplied from the horizontal axes to the drying tray as it is considered a waste since the drying force generated will not be effectively utilised to dry the raw berries. Gregoire (1984) has recommended that bottom-up airflow across the drying tray, which he claimed will yield the best drying effect. Therefore, the secondary warm air should be guided towards the bottom of the drying tray.

Besides, warm air presence at the bottom also implies more thorough drying process to the berries placed on the tray as it enables evaporation and heat-transfer at the backside of the berries, which are not exposed to the direct sunray.

3.1.2.2 The Berries Holding Capacity

In pepper production practices in Sarawak locale, a single harvest of an average smallholding from their matured pepper plant may give about five to fifteen kilograms of pepper berries. As immediate processing guarantees the best quality, the dryer should then need to accommodate such a quantity at a given process period. Since the design decision is favouring the mixed-mode configuration, wide netting is needed to hold the berries; especially for white peppercorn production.

3.1.2.3 The Size and Weight Matter of the Dryer

In general, by the nature of mankind and custom, most smallholdings would prefer to process their raw products at the site where it is harvested or somewhere near to their home for ease in applying, maintaining and safeguarding considerations. These places, however, do not always have an optimum drying environment and space. The limitation is usually caused by either the nature of terrain and land ownership.

A stationary direct solar dryer may take up considerably large space and is inflexible to realise optimum environmental condition like changes in solar azimuth angle in a calendar year. A portable dryer may solve the issue as it is moveable. The user can move and adjust the dryer to the best angle for optimum drying results. However, in order for the dryer to be portable, it must be considerably small in size and light enough to be moved.

The primary size issue of a dryer focuses on areas needed for collector absorber and drying chamber, which is the main operation supports in a proposed solar dryer. However, since the research also explores the use of long chimney to assist environment control in the drying chamber, the size of the lengthy pipe should then be counted too.

Weightiness is usually considered poison to portability; especially if it is powered solely by a man. In order to control the total weight of the dryer, strong but lightweight structured material is preferred as it has better size-to-weight ratio while offers strong structural support and portability. Example materials are plywood, hollow steel sections, plasticized polyvinyl chloride (uPVC) et cetera.

3.1.3 Sustainability Issue

Most of the low cost solar dryer uses wood strips and transparent polyethylene (PE) sheet as the material for frame and wall. Either steel mesh or PE mesh (or mosquito net) or cheese cloth are utilised as the netting to hold the tiny raw bits. Although those dryers have been reported to be working just fine, they may not be long lasting and have not guaranteed long term performance as the material can be degraded or damaged easily. Nonetheless, they have an advantage of easy replacement at a relatively cheap price.

In this research, the selection of material is primarily based on the same requirement background whilst some new materials are brought in to inspire a more durable and easy maintenance design. Although it will cause a rise in overall cost, the improvement in its sustainability in humid climate with better performance will still be considered worthwhile to invest.

A dryer optimized for peppercorn production can also be used for other food drying. Since the dryer is targeting an operating temperature of 45ºC to 55ºC it will be probably viable for other general foodstuff drying. Examples of those are grains and seeds. As the dryer is designed to be operating specifically in tropical rainforest, it should have no issue with remoistening dread caused by dew.

3.1.4 The Dryer Design Criterion

Solar dryers have existed for a long time and there are enormous numbers of trials on basic solar dryer design, which were proved feasible. In the case, it will be much simpler and realistic to optimize a dryer for certain climate condition instead of inventing a new system, which may have little benefit in return. An existing mixed-mode dryer has been reported working effectively in the tropical environment – The Hohenheim Tunnel dryer. Although it is powered by artificial source, it fulfils all necessary criteria that are yielding positive results under generic tropical climate.

The strength of the Hohenheim Tunnel dryer lies in its almost uninterrupted continuous airflow and promising hot air supply yield from its extreme large collector area. This enables it to supply enough heat flow inside the drying chamber. Another merit of such a dryer is the automatic heat flow management that permits the drying chamber to maintain a much stable operating temperature. The operation is controlled by the natural mean since the airflow and hot air production rate is both depending on the instantaneous solar radiation.

3.1.4.1 The Extension from Hohenheim Tunnel Dryer

Mastekbayeva *et al.* (1998) had presented an AIT dryer in Thailand. It is basically a Hohenheim dryer in a much compact size and it has proved to be working effectively in their local rainforest climate. However, the dryer has inherited the same issue: considerably huge in size and it will need a PV cell to operate the fan. Since the design in this research is intended to produce a portable pure passive system, some modifications need to be done.

To reduce the total area of the horizontal plan, a cascaded structure is used. The collector plane should be placed below the drying tray and the size will depend on the physical spread of the pepper berries. To achieve uniformity in drying, single layer tray is applied. Proper insulation below the dark colour painted collector is needed to achieve best collector efficiency. The collector efficiency is expected to be much lower as most of the collector area is partially covered by the tray mesh. However, it will be balanced by more effective drying as the warm air is penetrating vertically to the tray from the bottom rather than concentrated on horizontal rush in conventional Hohenheim dryer. Lower collector efficiency does also mean lower operating temperature, which may be a surplus in pepper drying. A conventional Hohenheim dryer may strike an instantaneous temperature of seventy centigrade which is too high for quality peppercorn production. High operating temperature will cause the loss of important chemical substances during the course of drying. By cascading structure, warm air will only produce moderate drying force to encourage evaporation and mass flow but may have minimum disturbance to the amount of chemical content inside the berries.

To produce unidirectional airflow inside the dryer as what happened in a conventional Hohenheim system, the air inlet and outlet of the dryer shall be placed at two separate ends of the tunnel. In this case, the inlet shall be placed at bottom side at one end and the outlet at the top end at another side; and as well, the tunnel shall be tilted to favour the natural convective flow. There will be two air paths in the dryer: a bottom-up drying force creates by the main solar collector to the drying tray and a horizontal draft from the inlet across the top side of the drying tray towards the outlet.

3.1.4.2 The Chimney Stack Effect

In Hohenheim dryer, the heat flow is enhanced and controlled by electric fan and the photovoltaic cells. In this research, the dryer will be utilising the solar chimney to mimic the operation. An additional compartment of solar collector with chimney shall be fitted to the outlet of the drying chamber. It is used as a supplementary heating compartment to pull the moist air from the source and expel it into the atmosphere. The rate of airflow is then controlled by the amount of the sunlight received. It shall give similar effect on both airflow and temperature profile as what happened in the Hohenheim dryer; though the effectiveness may be different.

3.1.4.3 The Wind Effect at Night

The rainforest climate offers plenty of massive air exchange at macro scale, so one can make use of this nature gift to prolong the drying operation. As the evaporation will happen until it reaches the equilibrium state at a given vapour pressure and at specific temperature, a drift of saturated air from the evaporation boundary layer caused by the pulling force at the dryer outlet will result in a gain in drying rate. Although the effect may be minor, yet it contributes to shorter overall drying time.

3.2 Pre-design Tests

There is a need to verify certain parameters which cannot be quantified by pure simulation. It has to be obtained physically at the local site. One of it is the effect of the surface wind blow to the long chimney. It will be particularly important for operation on windy nights. One should never neglect the wind effect to the chimney as it will cause an underestimate of the airing rate to the dryer (Afonso and Oliveira, 2000).

3.2.1 Fundamental of Pipe-flow measurement

A cylindrical chimney is normally utilized in updraft tower. The measurement of pipe flow is crucial to justify the flow rate. Based on the chapter about the fluid-flow in pipes published by Nakayama & Boucher (1999), he stated that in the pipe flow with a perfectly rounded entrance, the fluid flows will have approximately uniform velocity distribution across the diameter of the pipe close to the entrance in the pipe. As the flow goes further to downstream, the distributions of velocity across the cross-sectional area of the pipe become less uniform. The area of uniformity of flows happens near to the centre at the end of the pipe as the effect of the deceleration becomes more significant at the end of the inlet region. The length (L) of the inlet region in laminar flow is expressed by the following equations. It is estimated by Joseph Boussinesq in 1868 and verified with experimental studies by Nikuradse.

$$L = 0.065 \cdot Re \cdot d \tag{4}$$

For Turbulent flow, the experimental studies (by Nikuradse) gave the following result:

$$L = (25 \sim 40) \cdot d \tag{5}$$

From the studies, it is obvious that the measurement can be done without any major issues if the total volumetric flow rate across the pipe could be observed from the entrance as long as the measurement take place far enough from the tail of the inlet region. It does not matter whether there is turbulent flow or laminar flow in the pipe. In this case, a single point measurement is enough to reflect acceptable results.

3.2.2 The Effect of Airflow Chimney Results by Wind Effect

An experiment was conducted during March to April in 2009 to obtain the interactions between the atmospheric conditions and a chimney. The study was intended to discover the response of the use of the specific commercially available materials as the chimney supposed to work under the conditions of the tropical climate.

3.2.2.1 The Selection of Chimney Material

As the material to be use should be durable under projected operation temperature and resistant to local weather condition, the Unplasticized Polyvinyl Chloride (uPVC) pipe for constructions use was selected. An opening diameter of six-inch (160mm) was use due to cost and weight consideration. Smaller pipes do not fulfil the design criteria as their opening do not favour the airflow rate as explicitly stated in the studies done by Afonso & Oliveira (2000).

3.2.2.2 The Experimental Setup

A simple experiment was setup using a hollow pipe to investigate the effect of the pressure difference and air current induced. The main purpose is to validate the possibility of utilizing the same concept to improve airflow in the intended dryer. The experiment was arranged by using a six-inch diameter white-colour uPVC pipe installed vertically on a supported base at the open space surrounded by the tall buildings to simulate the presence of possible tall trees in the potential application destinations. The pipe was practically hanging up in the air at half a meter clearance above the ground. The upper end was partially covered by a cap to avoid the raindrops falling into the channel. A Testo hot-bulb anemometer is fitted inside the pipe near the lower end inlet, which connects to Testo 400 logger for periodic data acquisition purpose. The inlet was protected from crosswind with external vertical envelope to minimize the sensing deviation.

The data collection was done on a round-the-clock basis at two minutes interval for three continuous days for each different length of pipe. There were ten lengths from half-meter to five meters with half a meter difference. Weather condition over three days is observed and recorded for analyses purpose. The results obtained from logger are then average up for review. To benchmark the result, experiments were done at the same place and conditions using the same data collection method.

3.2.2.2 The Result and Discussion

From the observation, the weather conditions were monitored and they were fine with almost three consecutive warm days over the three-day experiment for almost all different lengths except for 1.5m, 3.0m, and 3.5m lengths, The experiment for these lengths were run interrupted due to almost two consecutive days of close intervening flash.

Table 3.1 shows the average airflow velocity pattern ranging from 0.5m/s to 5.0m/s. The reading had shown a positive change in average airflow velocity obtained as the length of the chimney increases to two meters. Beyond that height, the airflow rate starts to drop slightly and became unpredictable. The drop in mean airflow figure could be due to the head loss of the pipe. Based on the data shown in Table 3.1, one can conclude that the two-meter chimney is the most suitable length for the six-inch uPVC chimney as it generates stable airflow at the average airflow velocity of 0.31 m/s with the standard deviation of 0.18.

Table 3.1: The Speed of Airflow through the Pipe at different Chimney.

Chimney Length	**Maximum Airflow**	**Average Airflow**	**Standard Deviation**	**Medium**
(m)	***(m/s)***	***(m/s)***		***(m/s)***
0.5	0.71	0.19	0.0885	0.17
1.0	0.84	0.18	0.1400	0.17
1.5	1.79	0.25	0.2100	0.20
2.0	1.54	0.31	0.1800	0.28
2.5	1.12	0.26	0.1700	0.24
3.0	1.34	0.28	0.1969	0.24
3.5	1.15	0.29	0.2131	0.24
4.0	0.94	0.24	0.1700	0.21
4.5	1.06	0.31	0.2082	0.26
5.0	1.09	0.26	0.2126	0.22

There is also possible to extend the chimney length up to 2.5m. However, from the data presented, it seems not feasible to utilise taller chimneys as they do not earn any significant benefit besides increasing overall weights and may cause physical stability issue due to higher centre of gravity.

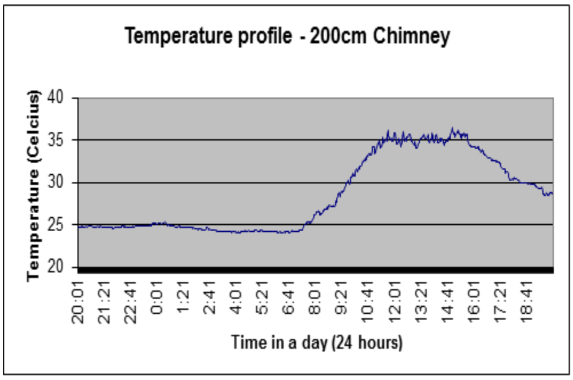


Figure 3.1a: Local Temperature over a Typical Warm Day (24-hour Period) for the Two-meter Chimney Experiment

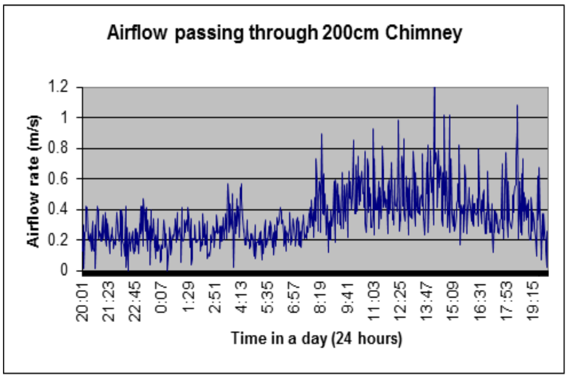


Figure 3.1b: Airflow Rate over a Typical Warm Day (24-hour Period) for the Two-meter Chimney Experiment

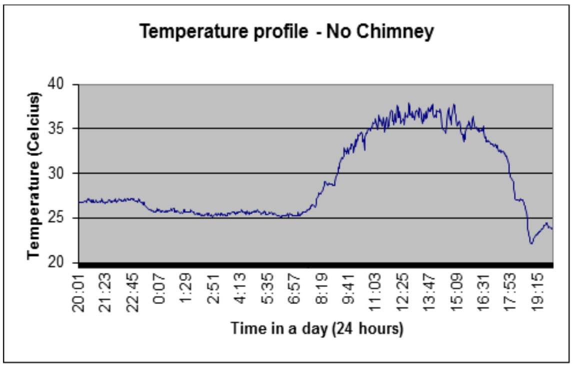


Figure 3.2a: Local Temperature over a Typical Warm Day (24-hour Period) for the Open Air Experiment

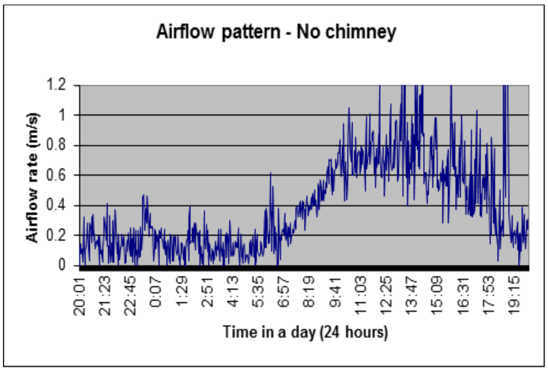


Figure 3.2b: Airflow Rate over a Typical Warm Day (24-hour Period) for the Open Air Experiment

Figures 3.1a and 3.1b shows the chart of the temperature and relative airflow rate recorded in a fine sunny day at the inlet of the two-meter chimney. It shows a stable airflow rate at approximately 0.2m/s over the night time. It also shows a positive response to the atmospheric temperature during the daylight, where the airflow rate increases with the temperature. The fluctuations are suspected to be caused by instantaneous wind blow at the top outlet of the chimney. From the figures, it suggested that the solar dryer fitted with a chimney of two-meter tall will be able to operate in the round-the-clock mode at an average airflow over a chimney of approximate $0.0066m^3/s$ mass transfer capacity at 0.2m/s airflow rate. Besides, the airflow readings also suggest a possibility of fighting against the effect of dew that is causing the re-wetting problem, which usually starts daily at twilight and ends around seven o'clock in the morning.

Reviewing Figures 3.2a and 3.2b, the airflow around the anemometer is higher and more responsive to the surrounding temperature compared to the airflow shown in Figure 3.1a and 3.1b. It could be causing by the free flow happening around the anemometer, which can be seen from the degree of fluctuation among the records shown in the chart. Moreover, the airflow pattern shown during the night time is not as good and stable as the values recorded in Figure 3.1b. This had further confirmed the benefit of implementing a long chimney to the dryer, which can minimise the re-wetting issue that happens when the air is stagnated.

The Effect of Dew

Apart from the above, physical observation on dew formation had given some valuable data to dryer design. With the relative humidity (RH) value on average more than 80% presence in local environment, the dew formation tends to occur with just little temperature change. The study records severe dew formation on both the inner and outer surface along the chimney. This happened between 0600 and 0700 hours and it depends on the weather condition. On a warm dry morning with clear sky, the dew formed very early and diminished faster; a cloudy sky will make the dew last longer. In rainy days, the dew does not form.

This phenomenon can be explained clearly based on the theory. It is caused by temperature variations that happened to be too significant and sudden between the surface of the solid material and the air. As the sun rises, the air was heated up faster than the solid material and it makes the air absorb more moisture around it to balance the RH in the atmosphere. When the wind blows, it causes the air to pass by the solid in which the solid is cooler than the air. Since the original RH is relatively high, excessive water content will form water drops and stack on the surface of the solid.

This incidence may happen on the surface of the pepper berries as well and it may not be possible to avoid. To reduce the chances of water engagement to the surface of the pepper berries, the airflow across the berries tray should be limited but not stopped so that the air inside the drying compartment can be heated up as soon as possible when the sun rises.

3.3 Pre-implementation Analysis

The physics of the solar energy transformation and resultant effects in a solar dryer have been discussed in the literature. The heat flux generated will heat up the berries and induce the bottom-up heat flow to encourage evaporation and remove the saturated air. A tilting arrangement of the tunnel will then guide the hot moist current to the base of the chimney before expelling to the atmosphere. Even so, there are two issues to be considered: the induced flow resulting from the wind-effect at the chimney outlet and the height of the tray in the drying chamber.

3.3.1 Induced Airflow by Wind-effect at Chimney Outlet

Simulation is a reliable tool that has been utilised for years in the industry to improve the old designs and creating new systems. The rapid prototyping option enables this research to visualise the effect of airflow pattern inside the tunnel chamber so that the optimum drying parameters can potentially be achieved resulting from the wind effect, which enables the dryer to work at minimal presence of heat flux. A study is done using Solidworks Flow Simulation on the crosswind presence at the chimney outlet and its effect to the induced flow inside the drying chamber.

The Simulation Setup

The wind induced airflow inside the dryer is done using Flow Simulation features in the Solidworks package. A cavity featuring a tunnel with equal cross-sectional area along the dryer length is modelled as the drying chamber. Inside the cavity, a big plate with slotted-holes representing the drying tray is placed with its width and length equals to the horizontal inner parameters of the drying area. The drying tray is fixed with a width of 1150mm and a length of 2200mm,which is the estimated size required for an average of five kilograms threshed raw pepper berries spread at a height of single berry. At one end of the tunnel, the cavity is extended to enable an air inlet opening at its bottom part. At another end of the tunnel, another extension is created with openings at the top side that connects to a low pressure source (virtual chimney) that simulates the induced airflow based on the parameters obtained in the pre-design test.

In all the simulation tests, the inlet of the dryer is set to environment pressure and the outlet is at the 0.2m/s with the assumption of a two-meter tall chimney is used and the operation is carried out in a fair weather night. The study examines three different vertical positions of the drying tray. The tray is spanning at twenty-five per cent to the height of the cavity at each trial starting from twenty-five per cent elevation. The study is concentrated on the steady-state response as the effect of the transient part of the wind is unpredictable. The simulation is configured to visualise the airflow patterns inside the drying chamber. It also studies the effect of the airflow inside the dryer as multiple chimneys are applied to enhance the mass exchanges.

The Effect of Multiple Chimneys to the Airflow Profile in the Drying Chamber

In the airflow study to the intended dryer, figures 3.3a to 3.3d have shown the results of the airflow patterns in the drying compartment with the drying tray elevated at the fifty per cent of the cavity height. In general, the airflow is more violent as the number of chimney increases from one (Figure 3.3a) to three (Figure 3.3b). Similar airflow pattern exists in the dryer of different settings; yet noticeable increase in airflow speed with much fierce turbulent formed near both the inlet (right side) and outlet (left compartment) in three-chimney configuration.

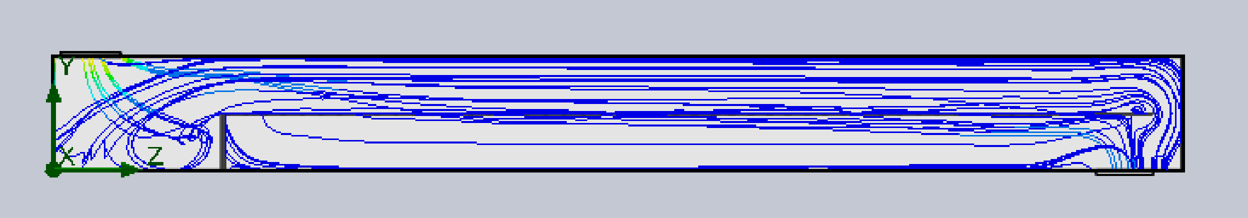


Figure 3.3a: Side view of the airflow simulation for a dryer with single chimney of 2.0m in length and 50% vertical elevation of drying tray

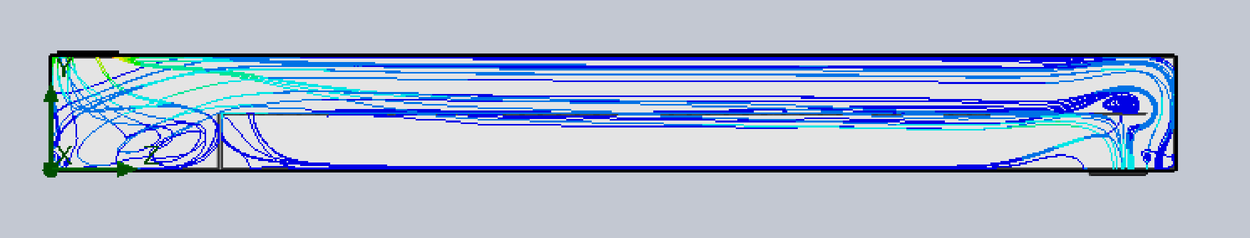


Figure 3.3b: Side view of the airflow simulation for a dryer with three (multiple) chimneys of 2.0m in length and 50% vertical elevation of drying tray

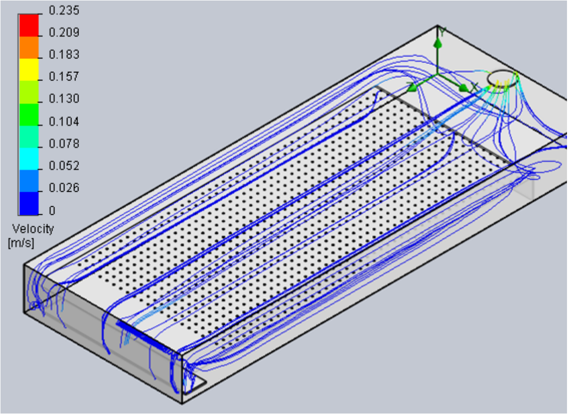


Figure 3.3c: Isometric view of the airflow simulation for a dryer with single chimney of 2.0m in length and 50% vertical elevation of drying tray

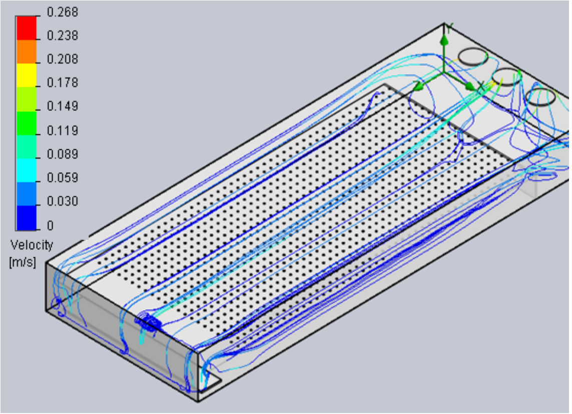


Figure 3.3d: Isometric view of the airflow simulation for a dryer with three (multiple) chimneys of 2.0m in length and 50% vertical elevation of drying tray

Since major turbulent flow does not seen to occur much at the drying chamber, it is assumed increasing numbers of chimney will favours drying rate as better mass flow occurs with enhance airflow rate.

3.3.1.1 The Effect of the Tray Height to the Airflow Profile in the Drying Chamber

Comparison in vertical position of the drying tray is made possible through simple simulated graphics. Figures 3.3b, 3.3d, and 3.4a to 3.4d demonstrate the differences in flow pattern response as the position of the drying tray is altered. Figure 3.4a and 3.4c illustrated the airflow pattern inside the dryer is not favourable to the drying and they look unsatisfactory compared to the other two configurations. This internal arrangement created turbulent at the inlet region of the entrance of the drying chamber and unfavourable airflow occurred below the tray at the front side of the drying chamber while much more intensive airflow occurred at the entrance side. This creates uneven drying pattern across the drying tray.

Moreover, high velocity airflow passes the drying chamber far above the drying tray towards the chimney. It causes a waste of scarce drying force that has not being utilised in drying operation. Simulation of both 50% (Figures 3.3b and 3.3d) and 75% (Figures 3.4b and 3.4d) tray elevation show better flow arrangement in the drying chamber for the drying of pepper berries.

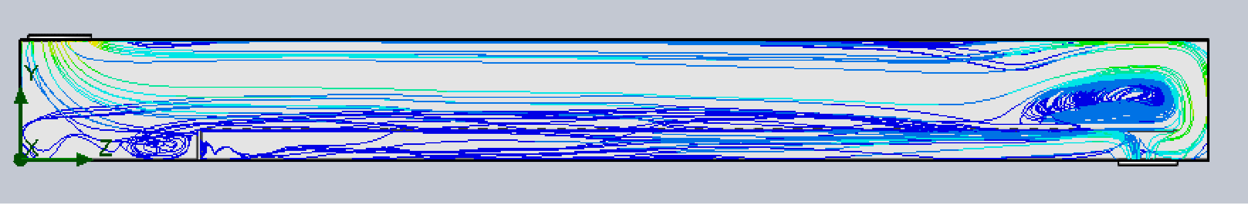


Figure 3.4a: Side view of the airflow simulation for a dryer with three chimneys of 2.0m in length and 25% vertical elevation of drying tray

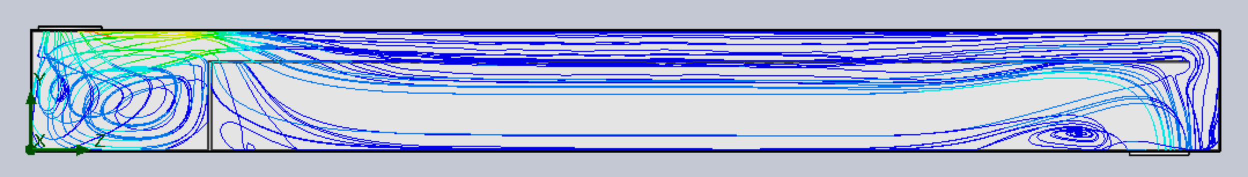


Figure 3.4b: Side view of the airflow simulation for a dryer with three chimneys of 2.0m in length and 75% vertical elevation of drying tray

From the airflow pattern shown in the figures, tray position at a 75% elevation gives the best distribution of air speed across the horizontal width of the dryer. Both 25% and 50% tray elevation shows a much higher air velocity (refer to the colour scale in Isometric view) at the centre region compared to both far horizontal ends. This will create a more uniform drying process across the horizontal axis. Besides, comparatively smoother flow pattern occurred along the length of the drying tray in case of 75% tray elevation arrangement over the 50% configuration shown in figures. It also suggests that this one is the better choice among all the three settings in the study.

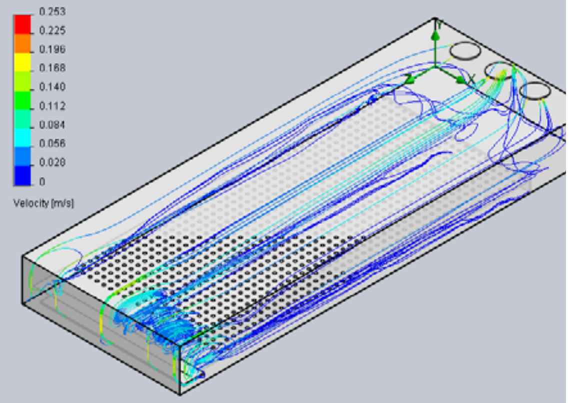


Figure 3.4c: Isometric view of the airflow simulation for a dryer with three chimneys of 2.0m in length and 25% vertical elevation of drying tray

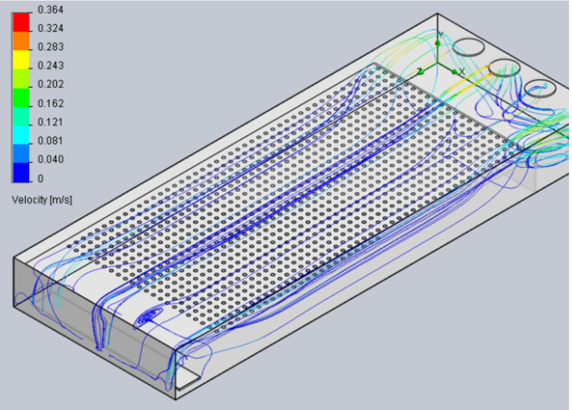


Figure 3.4d: Isometric view of the airflow simulation for a dryer with three chimneys of 2.0m in length and 75% vertical elevation of drying tray

The study, however, has revealed a weakness in the initial design. The simulation predicts that unavoidable turbulent flow occurs at elevated air velocity, which is concentrated at the inlet and the outlet of the drying tray. This effect could have potentially propagated to the drying chamber. To minimise the problem, a revised design was done.

A small modification was done by elevating the head room of the solar chimney base to reduce the turbulent effect against the front side of the drying tray. Figure 3.5a and 3.5c exhibits a clear view on the simulation result, which shows that the turbulent occurs only inside the chimney base rather than starting at the front-most section of the drying tray.

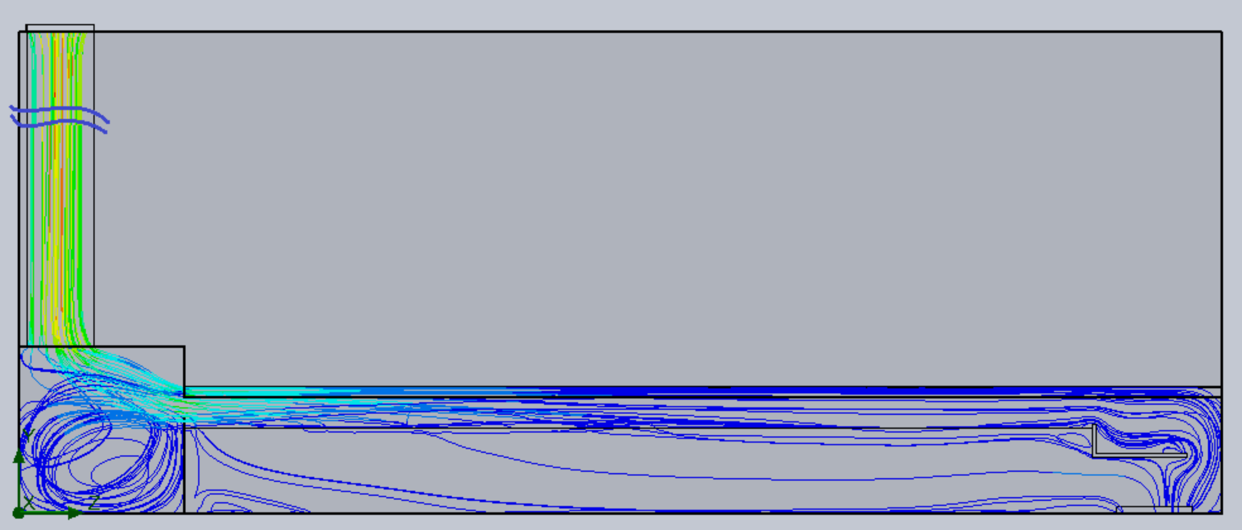


Figure 3.5a: Side view of the airflow simulation for the final dryer design

In addition, from figure 3.4b and 3.5c, it is clearly noticeable that the airflow distribution across the width of the drying tray seen flat compare to the previous design shown in figure 3.4d. This result is partially contributed by the inflated design on the dryer cover located right above the drying chamber. The design also results shorter dryer length by five centimetres due to the shorter chimney base.

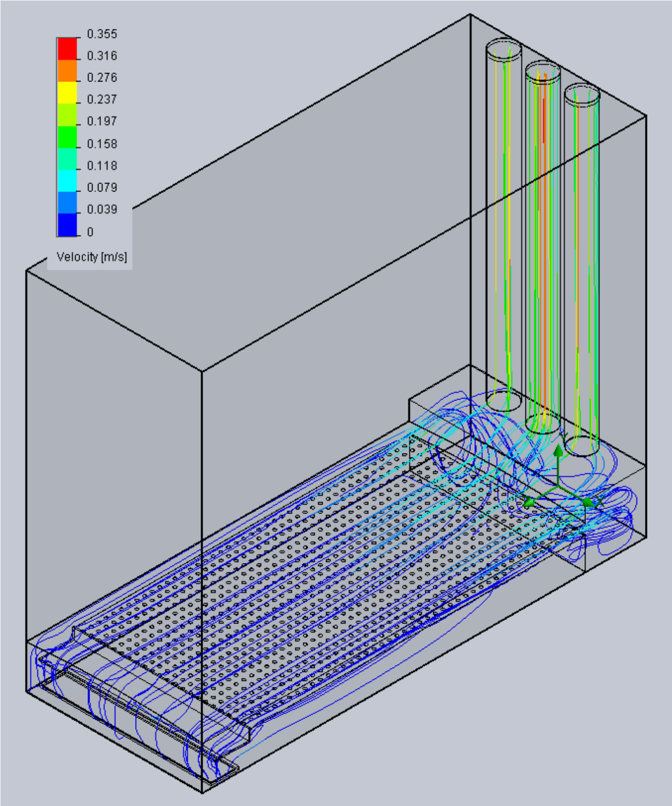


Figure 3.5b: Isometric view of the airflow simulation for the final dryer design

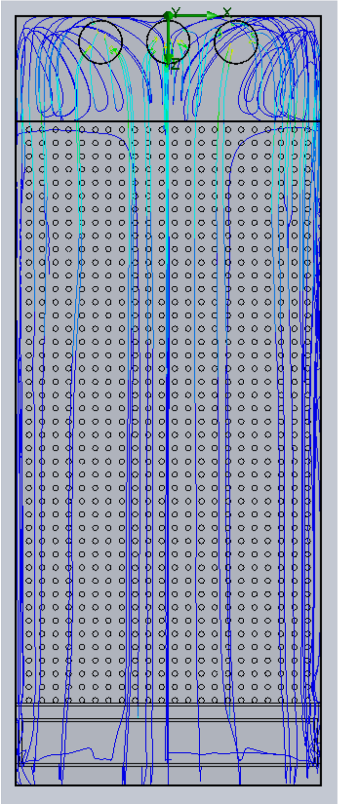


Figure 3.5c: Plan view of the airflow simulation for the final dryer design

To minimise the turbulent effect at the inlet region, the inlet heating region is lowered. It divided the compartment into two equal regions. It creates an opening to the drying chamber, which has minimised the drastic flow as shown in Figure 3.4b. Figure 3.5a shows the result for this case.

3.3.2 System Configuration

Figure 3.6 and Figure 3.9a show the layout and actual view of the proposed solar dryer. It features a portable dryer with a changeable chimney length aiming for peppercorn production in the rainforest climate. It is designed to operate twenty-four hours round the clock in all-weather condition. The dryer consists of four parts: drying chamber; solar chimney; warm air supply; and moveable chassis. Detailed description will be presented in following paragraphs.

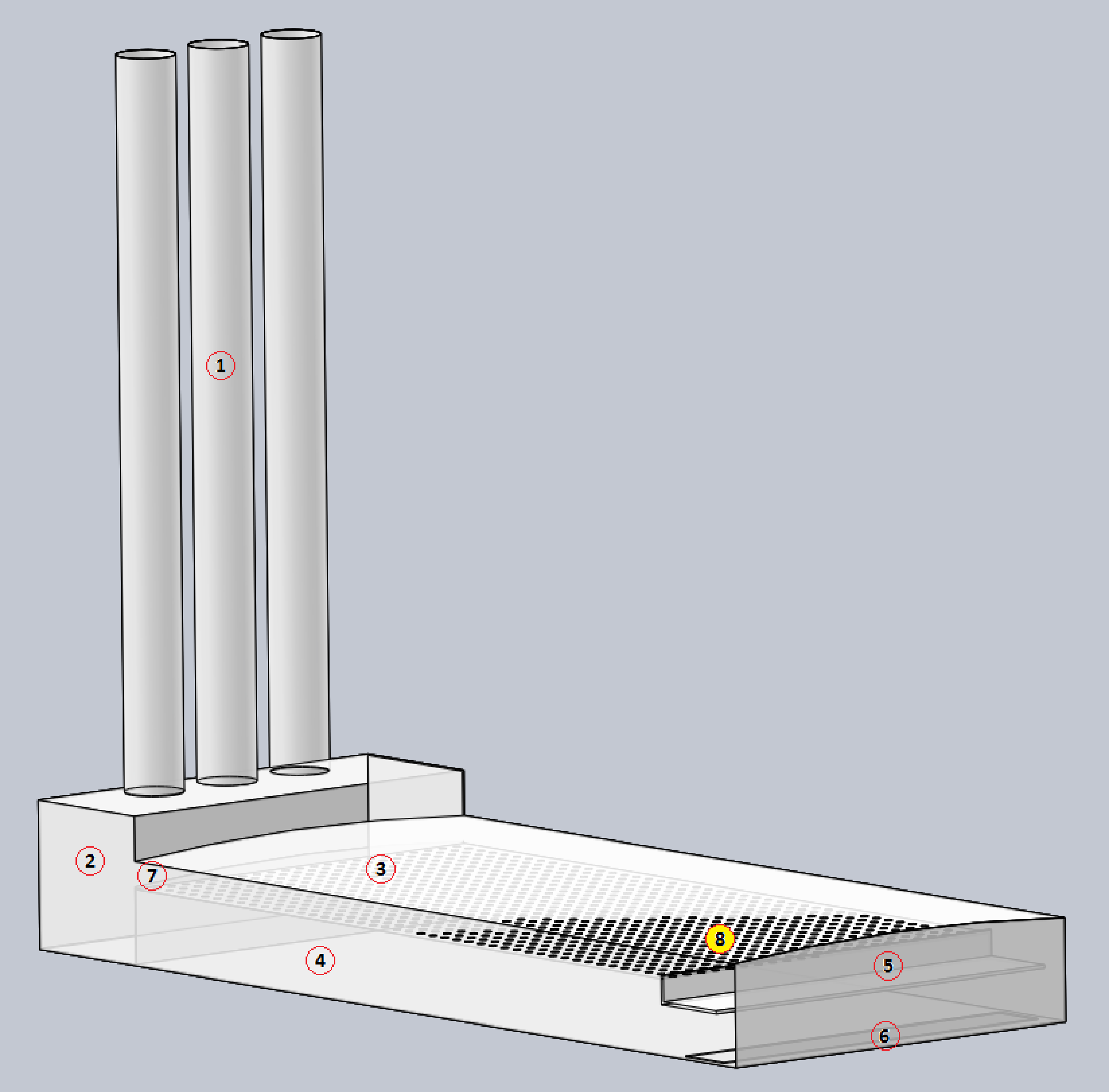


Figure 3.6: The body layout of the proposed mixed-mode solar tunnel dryer that utilises varies chimney length to control the internal climate

(1) Chimney (outlet)	**(5) Inlet heating region (drying chamber inlet)**
(2) Chimney base	**(6) Fresh air inlet**
(3) Drying Chamber (region above the tray)	**(7) Exit vent for drying chamber**
(4) Solar collector (region below the tray)	**(8) Mesh tray**

3.3.2.1 The Drying Chamber

The drying chamber is assembled in a tunnel with two sides cover by 9mm thick plywood on a ladder steel frame locked to the dryer base. The top side of the chamber is protected by 5mm cast acrylic sheet at an inflated design. The chamber shares the airspace with the solar collector compartment at its bottom side. Both the front end and back end is connected to the solar chimney and fresh air inlet compartments.

The drying tray is presented by a coarse stainless steel mesh with an inflate design. It is supported by the steel frame as described earlier. The clearance between the acrylic cover and the tray is 75mm. This allows enough airspace for both pepper spikes and berries to spread over the tray in single layer.

In the design, cast acrylic sheet was chosen because it is weatherproof, shapable, and tougher but yet lighter (less than half of the weight) than glass. Although it is slightly more expensive than generic glass material, it has an overall advantage in thermal insulation (0.19w/m.k) and transmittance (92%). In term of emissivity, acrylic scores 0.92 compare to glass (0.90), which means it can retain more heat inside the dryer for more effective drying. Unless an expensive low-iron glass is customised for the purpose, general acrylic will perform better in a mobile solar dryer.

3.3.2.2 The Secondary Warm Air Supply

The tunnel dryer has two separate compartments producing warm air to assist the drying process. One of them is located right above the fresh air inlet and another below the drying tray. The fresh air is supplied through two adjacent channels at the inlet to both compartments separated by the plywood, which form one part of the structure.

The first configuration lets the fresh cool air to pass through a 200mm blackened flat plywood panel to feed the drying compartment. Its purpose is to pre-heat the air that moves horizontally across the topside of the drying tray. This opening has the pressure balancing effect when there is a pulling force at the front end of the drying chamber caused by either the wind effect or stack effect.

The second configuration is the main secondary warm air supply that contributes to the direct drying force. The compartment is a rectangular box with its top side covered by the mesh tray and the bottom side laid with 9mm black-painted flat waterproof plywood which served as part of the structure as well as the absorber of the solar collector. The cast acrylic sheet of 5mm thickness and a height of 150mm are fixed at the two sides along the length of the compartment to allow penetration of sunlight to the absorber. An opening is created facing the fresh air inlet and a plywood wall is installed at the opposite side to separate the solar chimney and the drying region.

The absorber plane located at average distance of 200mm below the drying tray will heat up the fresh cool air during the daylight. The buoyant warm air will then float towards the drying tray as the secondary drying force to enhance the surface evaporation at the berries' pericarp. Continuous supply of warm air due to convection will help to transport the saturated air from the drying tray upward to the horizontal air stream, which will later float towards the exit.

Portability and cost issues have imposed a vertical limit to the compartment design. Although it may sacrifice the heat recovery during the daylight, it should not cause huge deficiency as the primary drying force is depending on the direct radiation.

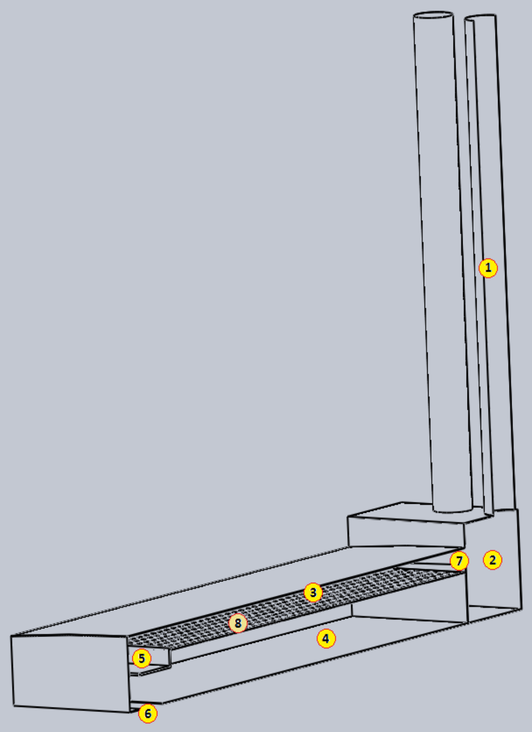


Figure 3.7: The Section-cut drawing for the proposed mixed-mode solar tunnel

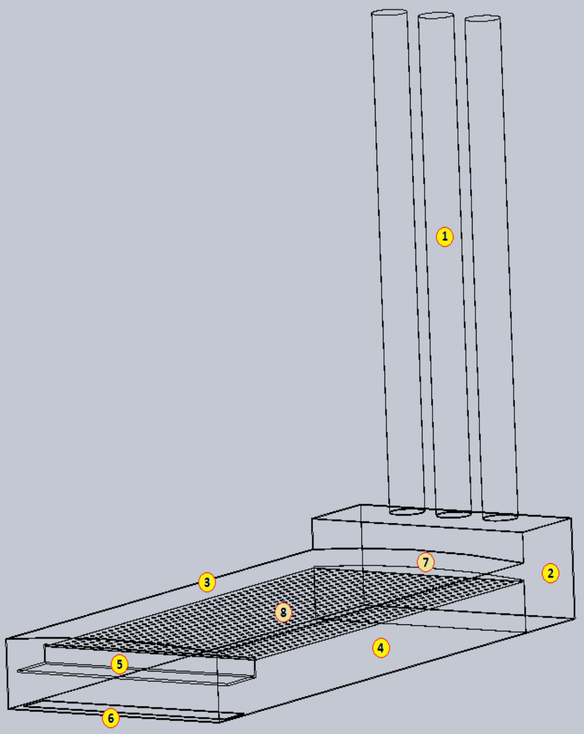


Figure 3.8: The component view of the proposed mixed-mode solar tunnel dryer

3.3.2.3 The Solar Chimney – Mass Flow Outlet

The solar chimney is the outlet of the dryer, which is attached to the exit vent of the drying chamber. It consists of only two components: the chimneys and a buffer box. The chimney is made of uPVC pipe of 160mm (six-inch) in diameter and the buffer box is made of 9mm waterproof plywood and 5mm cast acrylic sheet.

The chimney controls the internal climate by limiting the amount of airflow passing through it and the buffer box collects the buoyant hot moist air from the drying chamber before expelling to the atmosphere. Having enhanced updraft, the buffer is designed as a secondary solar collector. The solar gain in the buffer box together with the specific height of chimney can induce different mass flow rate.

3.3.2.4 The Moveable Chassis

Basically, the dryer is sitting on the chassis; which it loads by all of its weight directly to the main frame. The chassis has to be strong but lightweight so that it can be easily moved by a man. A ladder frame structure is used where two symmetrical rectangle steel hollow sections (25mm x 50mm) are linked by four cross-members of the same material to form a rectangle base. The frame has a fixed V-shape wheel support near the front end. This is fitted with two thirteen-inch wheelbarrow's wheel at each side. Near the back end of the frame, two height-adjustable fixed stands are welded at each horizontal ends. At the back end of the frame, there is a handle designed to move the dryer.

The physical mass of the dryer is designed to load primarily to the two wheels. It is like a huge wheelbarrow, which will ease the transportation by requiring only minimal lifting effort before the pull, push, or swing actions. The design does enable the operator to move the dryer effortlessly from one location to another even if the terrain is mildly sloped. The user can swing the dryer to get the desired angle to face the sun for optimum solar gain. The user can easily turn the dryer to either the left or right (Figure 3.9b) for a better position facing the sunray.

The chassis is designed to obtain a five per cent tilt for optimum solar gain and to achieve smoother heat flow inside the drying chamber. Since the rural terrain is usually uneven, the adjustable stand will play an important role to ensure a near total balance in both horizontal direction and maintaining a correct tilt angle.

Figure 3.9a: The actual view of the proposed mixed-mode solar tunnel dryer that utilises varies chimney length to control the internal climate

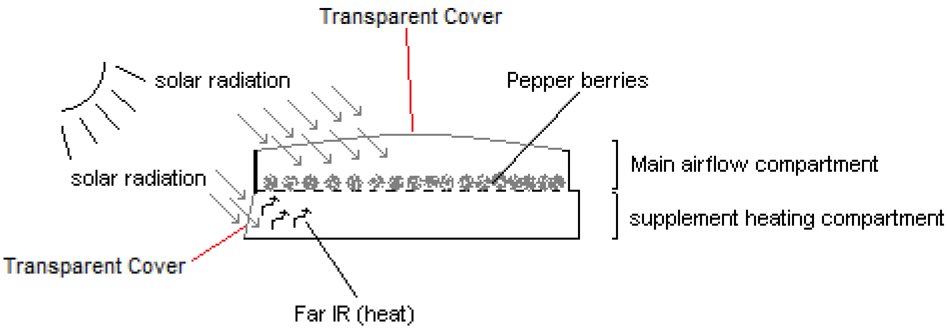


Figure 3.9b: The conceptual operation of the proposed mixed-mode solar tunnel dryer (cross section view).

3.4 The Experiment Setup on Final Model

Mastekbayeva *et al.* (1998) did the performance tests on their AIT dryer by measuring following parameters: Radiation incident on the dryer; air temperature presence at various locations; and, the air velocity. They used k-type thermocouples to obtain both the dry-bulb and wet-bulb temperatures located at fresh air inlets, exit point of the solar collector and drying chamber. Another two dry-bulb temperature are measured at the middle of each compartment. The experiment was executed from 0800 to 1700 at five minutes interval using a logger. The relative humidity data is determined by the dry-bulb and wet bulb temperatures. The solar incident data was acquired from the meteorology station.

In their experiment, they performed both no load and full load tests for chilies. For full load test, the daily drying rate is estimated by obtaining the weight loss at the end of each day. Natural sun drying samples were taken to benchmark performance of the dryer.

From the description on above, it has shown that the drying characteristic study can be done through obtaining the air velocity and the temperature and humidity profile inside the solar collector and drying chamber. The performance of the dryer can be benchmarked by comparing the weight loss and time taken against the natural sun drying samples. In fact, this performance assessment for a solar dryer has been supported by Purohit *et al.* (2006) and Imre (2007).

In this research since no power supply available during the actual field test, continuous data acquisition on the final model cannot be carried out. However, periodic observations were done and recorded on certain perspectives. To capture a real image of the operation parameters, a study was done for no load test to the final model at the outdoor space near the laboratory using continuous data acquisition. The intention was to get a preview on what is happening in the dryer so that it explains the periodic data obtained in the field test.

3.4.1 Investigation on the Effect of a Chimney to the Model Dryer

An experimental study was carried out during December 2009 to pick up on the effect of the presence of tall chimney to the drying condition inside the drying chamber. The experiment was implemented at no load condition. The study tried to discover three parameters at different atmospheric condition. Those parameters were the average airflow passing through the chimney, the temperature and humidity profile inside the dryer at different compartments. The experiments were conducted on full sunny, mixed weather, and wet days.

An airflow logger consists of a Testo 400 electronic logger coupled with a hot bulb anemometer. It is installed at the entrance of the centre chimney to obtain the average flow rate and air temperature passing through the chimney. Although the chimney base is located at the same height, in the practice the dryer may tend to tilt along the width of the dryer due to uneven ground surface. It is assumed that the flow rate obtained from the centre chimney shall show the average value and this should be applicable for all three to estimate the flow rate at the exit vent of the drying chamber.

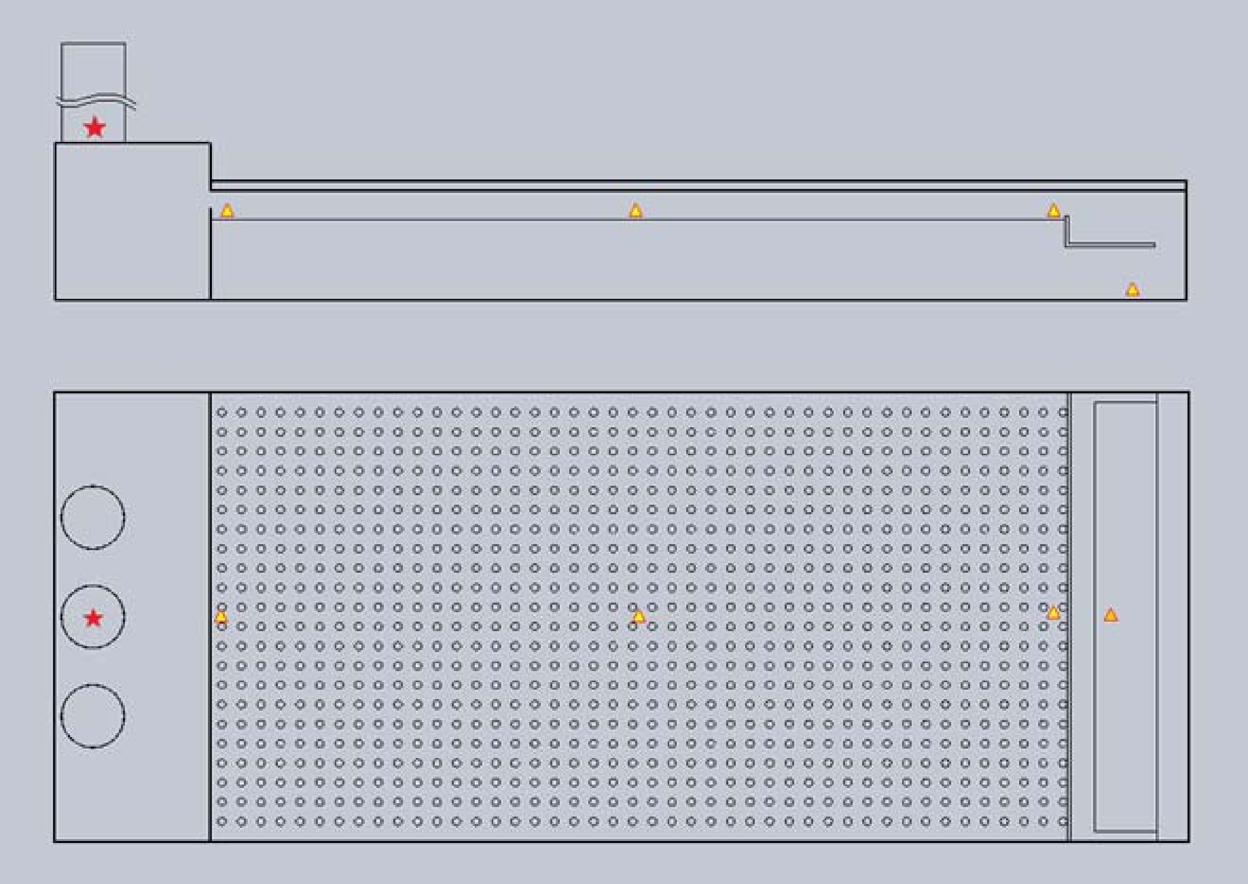


Figure 3.10: The sensor distribution positions in the proposed dryer.

To measure the temperature and humidity profile inside the dryer, four units of Sensirion humidity sensors are implemented. The SHT75 digital humidity sensor has a 14bits resolution in temperature measurement and 12bits for humidity data. The sensors are coupled to the custom-made Intel 8051 microcontroller acquisition interface that logged the information directly into the personal computer at two minutes interval. The distribution of the sensors are in a straight line located in the middle of the width span starting from the fresh air inlet – the upstream of the drying tray, middle of the tray, and followed by downstream right before the partition between the drying chamber and the solar chimney compartment. The remaining one is fitted to the inner side of the fresh air inlet opening for measuring the surrounding data. Figure 3.10 demonstrates the distribution of sensors in graphical view.

The experiment was held at the open air space in the car park near the laboratory where there is access to power source. The experiment was executed on a round the clock basis. It is assumed that the middle line will give an average result for drying characteristics study as this is the neutral axis along the drying airflow that will have minimum disturbance regardless of sun position during the daylight. Moreover, as the experiment was done only for no load condition, the value would have, ideally, no difference between the top side and bottom side of the tray. Therefore, one set of sensor is enough to depict the profile. The results and discussions are presented in Chapter 4.

3.4.2 Dryer Field Tests

The field test was carried out on the open grass ground in the proposed football field in Swinburne University of Technology, Sarawak campus. It simulated the possible open air field in the rural village and it is intended to collect data at the dryer's optimum potential since the open space would obtain full wind load and optimum sunshine. No data acquisition module was attached to the system due to power source issue. The experiment involves only the drying of whole black peppercorn since it required longer drying period compared to white peppercorn production.

3.4.2.1 General Loading Procedure

In the drying test, a few big batches of hand-picked fresh pepper (with berries on stem) were obtained from Serian district (Kuching Division) through Malaysian Pepper Board (MPB). Upon receiving, the pepper was divided into smaller packets and stored in the refrigerator. A separate 200g of threshed pepper berries were packed and send to MPB Central Testing Laboratory for chemical analysis. All the experiments should start in the evening with the assumption that the dryer would operate effectively during the night.

Figure 3.11a: The back view of the proposed dryer - open for loading

Figure 3.11b: The side view of the proposed dryer - open for loading

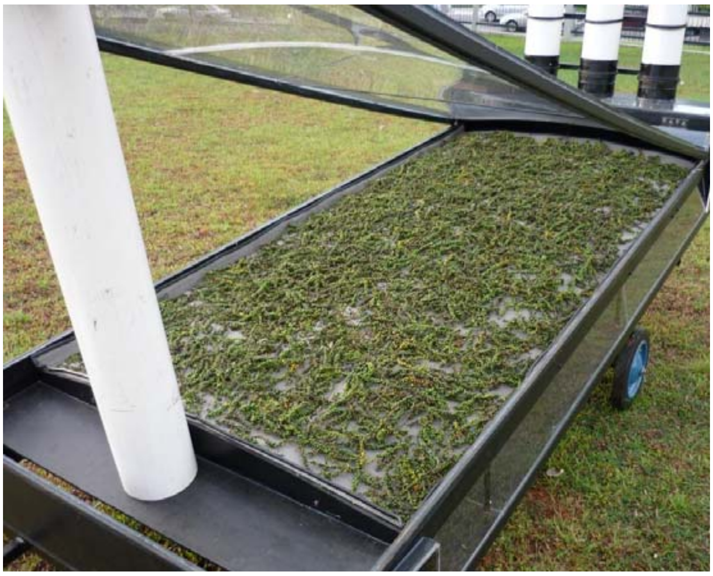


Figure 3.11c: The view of an approximate 12.5kgs of pepper berries with stem (Semongok Emas cultivar) is loaded in the proposed dryer

The loading and unloading of pepper was done by first unscrewing the two wing-nuts at each side across the width of the dryer at the back end of the top cover as circled in yellow in Figure 3.11b. Then, it required user to lift the acrylic cover and install a support to it. Seven kilograms of pepper spike (berries on stem) was spread over the tray from the two sides of the dryer. Single layer of spikes or berries is preferred in practice. Once the loading was done, the operator shall remove the cover support, close the cover and fasten the wing-nuts.

An earlier trial was done showing that the there was no significant difference between 0.2m to 0.5m of chimney lengths, therefore 0.5m length was not carried out in the batch test because of limited fresh pepper supply. Another limiting factor was the storing period of the fresh berries. The experiment was concentrated mainly on the 0.2m, 1m, and 2m of chimney lengths. The chimney was changed to accommodate different test configurations. Four different lengths of chimney were presented in this report – 0.2m, 1m, 1.5m and 2.0m.

The white-coloured chimneys can be twisted and unplugged in upwards direction to remove them from the base. To install the chimneys, simply plunge it back to the short blackened chimney holder. By simple re-coupling action, the joining part of the uPVC pipe and the holder offers a close-to-air-tight connections and it does never require any third party filler to assist sealing.

A slight adjustment to the dryer body is required to maintain a five degree tilting. It can be done by adjusting the translation screw at the fixed-stand. The adjustment shall only be done after the dryer has swung to the correct angle for maximum solar gain. To achieve that, either side of the dryer has to face the morning at perpendicular to the direction of the sunrise so that minimal shadow appears in the drying chamber and the solar collector.

3.4.2.2 Validation – Natural Open Sun Drying

To validate the performance claimed, natural sun drying experiment was carried out in parallel with the solar dryer test. The conventional drying was done by spreading a reduced amount of pepper spikes over gunny bags laid on the grass ground near the dryer. The gunny bags are loaded using stones at four sides to avoid accidental flip-over caused by sudden strong wind.

Figure 3.12: The sample view of natural sun drying pepper berries (Semongok Emas cultivar) with stem loaded on the plastic gunny bags.

The sun drying operation started after eight in the morning to avoid condensation and the berries are stored back into plastic gunny bag around six in the evening. Besides, the pepper would be collected back when it would be raining.

3.4.2.3 Measuring Concept and Practices

The field test determined the performance of the dryer primarily by the drying time over different weather conditions. Chemical content is also evaluated to conclude the best configuration at different weather condition.

The weight readings for the dryer were taken twice both at seven o'clock in the morning and in the evening. The product was collected in a plastic container and was weighted using electronic scale with 0.1g precision. After readings were taken, the product was shuffled and loaded back to the dryer. On the other hand, for natural sun drying, one weight reading was taken around eight o'clock in the morning before the dying process started. Another reading was taken around six o'clock in the evening after the product has been recovered from the field.

Physical weather conditions during the experimental days were recorded to explore the effect of the surrounding circumstance to the dryer so that its internal environment can be predicted. The operation was done together with physical observations by bare eyes and hand to the berries before unloading for weight reading.

The drying process was continued until the product had weight less than 33% of the original weight (wet basis). Then, they were packed and sent for chemical analysis in MPB Central Testing Laboratory. The results and relevant discussion is presented in Chapter 4.

CHAPTER 4: ANALYSIS

This chapter presents the results of the tests carried out in the experiments, which evaluates the performance of the actual model dryer. Discussions are done on each finding.

4.1 The Effect of a Chimney Presence on a Dryer

Figures 4.1 to 4.3 demonstrate the internal drying environment for the dryer operated under different distinct weather condition namely, Sunny, mixed-weather, and raining day. The meteorological data for the region (broad) for the respective experiments is shown in Table 4.1.

Table 4.1: Meteorology data of the experiment presented in figures 4.1 to 4.3 from the nearby weather station (Kuching) for reference.

Weather Condition	Sunny	Mixed	Raining
Daily Solar radiation (MJ/m^2)	22.20	17.88	11.04
Daily Mean Cloud Cover (oktas)	6.8	7.0	7.0
Daily Mean Wind (m/s)	1.8	1.6	1.7
Daily Mean RH (%)	76.5	90.6	88.2
Daily Mean Surface Air Temperature (ºC)	28.2	25.8	26.6
Daily Total Rainfall Amount (mm)	0.0	60.6	54.4

From Figures 4.1, 4.2 and 4.3, it is noticed that there is minimal heating effect at the entrance or inlet of the drying tray. The temperature rose more intensely along the tray towards the exit or outlet region. Hot air presence at the exit point reduces the relative humidity (RH) figures a lot compared to the entry point, especially during warmer days. On the other hand, the inner drying atmosphere at the entrance region fluctuates according to the inlet fresh air; it stabilises along the tray to the exit. The findings show similar data trend in the study done by Ferreira *et al.* (2008) who concluded the effective drying happens only at the region near to the chimney base.

The figures also depicted that the model dryer has effectively extended the drying period compared to natural sun drying (can be represented by the inlet temperature and inlet RH graph). This is particularly significantly in sunny days where the inner temperature and RH value only flattened after 8pm, which is about one hour after dusk. This means a prolonged period of drying in the same single day can be expected, which would benefit in terms of the total drying time.

The dryer experience little airspace heating capability during a cooler day. Figure 4.3 however shows the dryer can maintain a stable and even distributed drying environment over the daylight period compared to warmer days. In this case, pepper drying under this environment shall depend much on the direct radiation rather than the supplementary warm air supplies. Yet on a hot day, shuffling may be require to realise more even rate of drying over the product located at upstream and downstream.

From figure 4.1, the dryer has shown an elevated temperature (>55ºC) over two hours span at the exit region of the drying tray. This may lead to extraction of additional valuable chemical content and causing poorer quality peppercorn. This however, does not happen in a mixed weather and wet days. In the case, shorter chimney may need to be considered when the drying is done during a dry hot sunny day.

The experimental results have omitted the airflow data as it could not depict properly the flow pattern during the daylight period. The logger recorded a zero value a little while after the sun rose. Such incidence happens usually much earlier on a warm morning compared to a cold day. The acquisition system, however, works during the night. The issue is suspected to lie with the operating limits of a hot bulb anemometer in warm dry air; nonetheless, neither in the literature nor the product datasheet has addressed this issue. In the case, the presence of airflow caused by wind can be depicted only through the fluctuations in relative humidity values in minor scale. The only question remained was the evidence of how much a solar chimney may increase the airflow rate in the dryer.

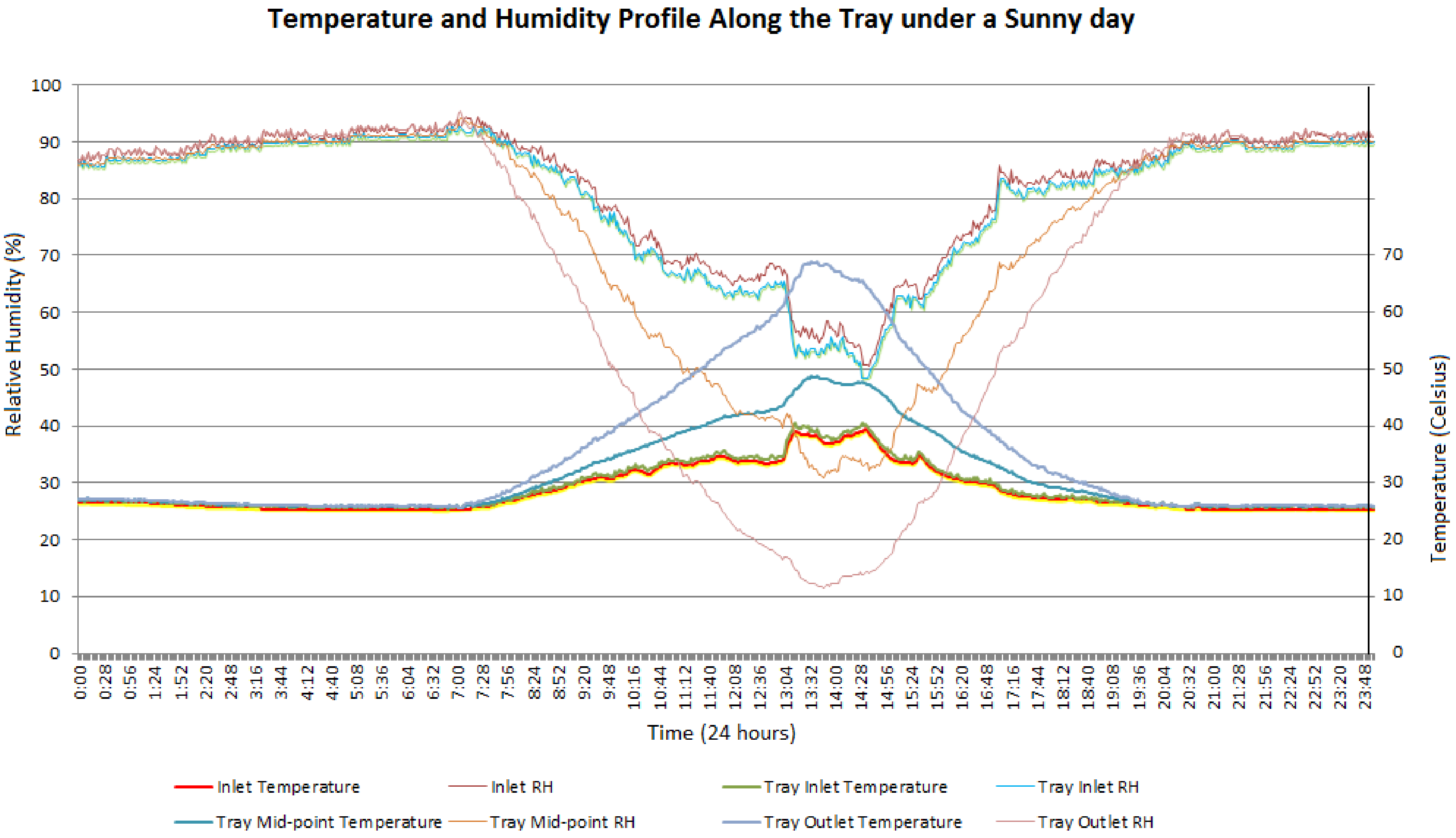


Figure 4.1: The environmental profile inside the drying chamber under a typical hot sunny day (2.0m chimney)

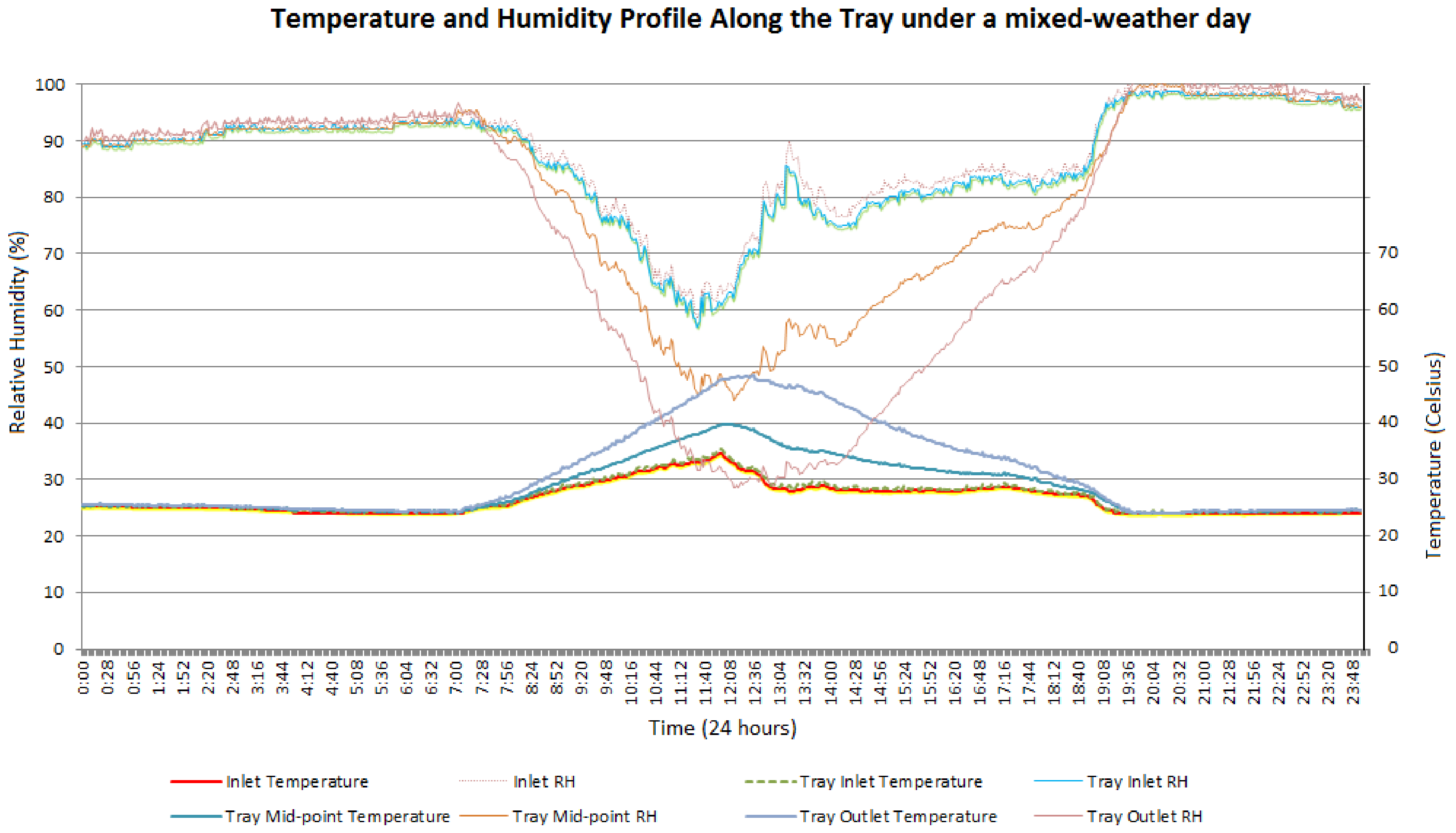


Figure 4.2: The environmental profile inside the drying chamber under a typical mixed-weather day (2.0m chimney)

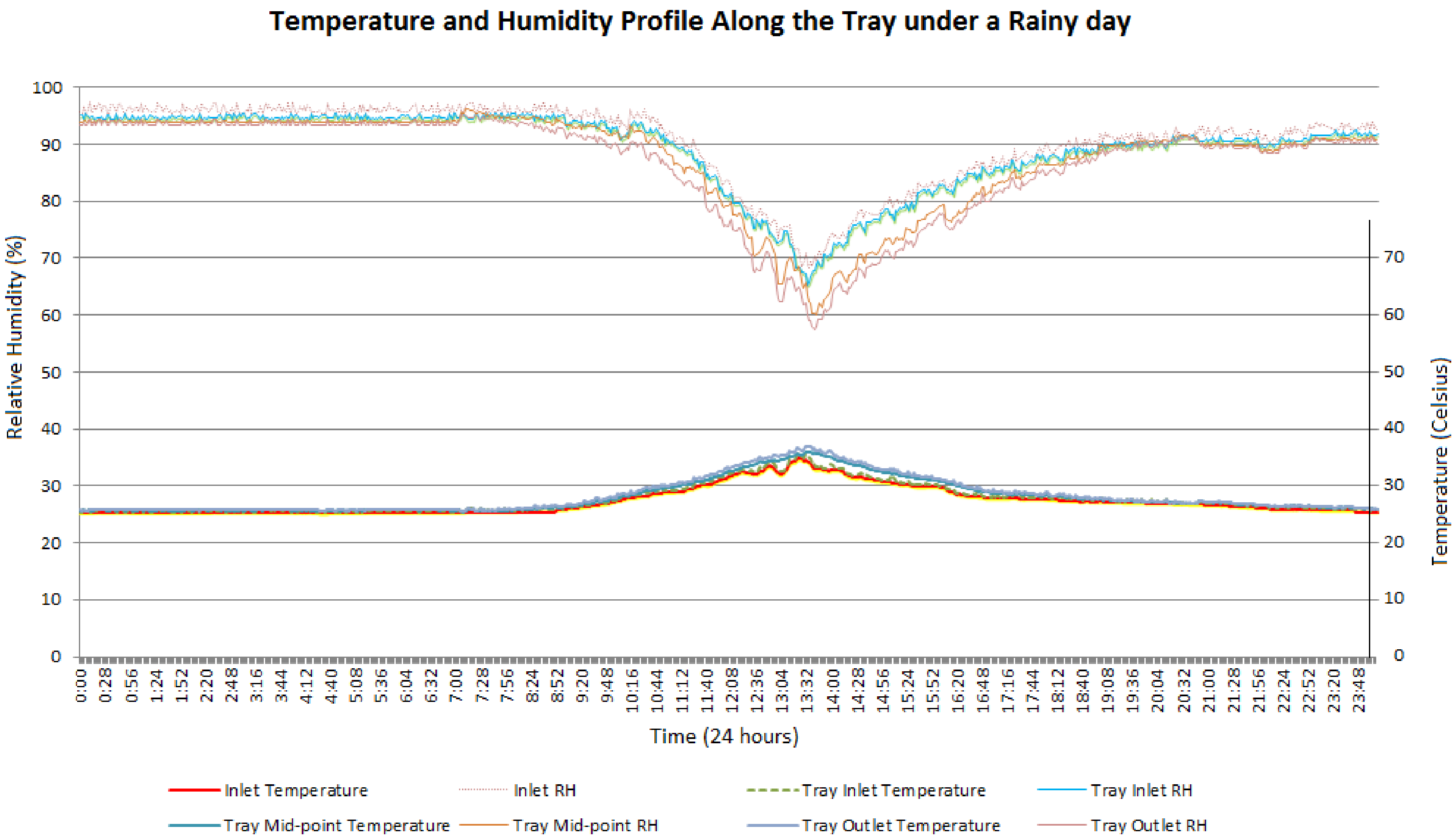


Figure 4.3: The environmental profile inside the drying chamber under a typical wet day (2.0m chimney)

4.2 The Field Test Results

The experiments were carried out during July 2009 to examine the usability of the model as claimed in the design. Since the storing period for fresh raw pepper berries can only be stretched over a maximum of eleven days (Chih and Sim, 1977), the same batch of the berries is used to ensure a better validity of the result. Figure 4.4 presents a view of dryer in actual operation condition.

Figure 4.4: The dryer operates in a sunny day - picture taken during low sunlight moment to reduce reflection

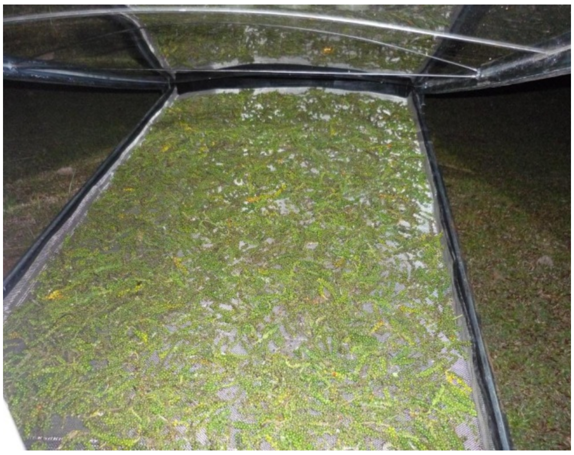


Figure 4.5a: A view to the drying tray during the first evening (fresh spikes) in a fine evening after a hot sunny day (2m chimney setting)

Figure 4.5b: A view to the drying tray during the first morning after in a fine night (2m chimney setting)

Figure 4.5c: A partial view to the drying tray after the first full day drying under a hot sunny day (2m chimney setting)

Figure 4.5d: A partial view to the drying tray at the early afternoon (1pm) on the second day. The pepper is left until 3pm under cloudy afternoon (2m chimney setting)

Figures 4.5a to 4.5d present the views in different drying stages over one and a half days drying period under a two-meter chimney configuration. The results are prensented in Table 4.2. Figures 4.6a and 4.6b shows the difference of the drying results after the first full sunny day. Although one cannot clearly differentiate much in term of physical shrinkage even in a close up view, a broader view (Figure 4.5c and Figure 4.6b) has illustrates the dryer has a much better drying capability over the natural sun drying. The model dryer took about one-half of the total drying time for the conventional drying practices under a bright sunny day. From the selected chemical analysis done on both samples, the sample in the dryer obtained a better results in both volatile oil, non-volatile ether extract and Piperine content, which denoted achieving better aroma and pungency.

Comparing the drying experiment done for 0.2m, 1.0m, and 2.0m chimneys under similar weather condition, 1.0m length show a much better overall result in the batch followed by 2.0m chimney and finally the 0.2m. From the result, it seems chimney length at 1.0m tall offers the best drying environment in the case of the sunny days. However, it may not perform well in a wet day since the sample shows a total mass increases obtained in the second morning. The negative pecentage shown in Table 4.2 for the batch numbered SWB/DT/B4/01SC1M demonstrates a re-moistening effect to the berries. This issue does not occur in batch numbered SWB/DT/B2/02/02, which experienced very wet surroundings during the experiment.

Figure 4.6a: A close up view to the sample from the dryer after the first full day drying under a hot sunny day

Figure 4.6b: A close up view to the sample dried under natural sun drying after the first full day drying under a hot sunny day

From the observation, longer chimney (2.0m pipe) will perform well during unfavourable weather condition. Re-wetting was observed after weight reduction beyond 54% to 60%, which most other configuration did; as shown in Table 4.2. The situation is even worse if the weather conditions in the daylight are unfavourable; like the sample marked SWB/DT/B4/01SC1M5. On the other hand, physical observation have shown an unfavourable outcome on using of 2.0m chimney in hot dry day (SWB/DT/B4/01DR) as there is a clear dividing line that separates the over dried (downstream – deep brownish) and partially dried (upstream – black) peppercorn.

From physical observations, the berries resided in the dryer with shorter chimney that operates in a unfavourable day or night often gives a moist feeling compared to those dried under 2.0m chimney configuration. The conditions are particularly bad during the wet early morning (SWB/DT/B4/01NC), where the surface condensation can be observed on some berries expecially those located near the fresh air inlet. A longer chimney can minimise the re-moitening or rewetting effect. This happens due to the pipe head, which limits the free exchange of the saturated air presence in the atmosphere outside the dryer. The deduction is based on the percentage reduction obtained by 1.0m and 2.0m chimneys on the first daylight. As the 2.0m chimney gave better average internal temperature compared to the 1.0m chimney, it has better drying capability; especially in conditions when there is massive water or moisture presence in the close surrounding. Higher airflow will always offer better efficiency unless the temperature difference is extremely high and this has been proven in many literature.

Table 4.2: Local field test results comparison chart

Chimney Pipe Length	2.0m (Mixed)	2.0m (Dry)	1.5m (Wet)	1.0m (Dry)	0.2m (Dry)	Natural Sun (Dry)	Natural Sun Drying (Wet)	
Batch Number	SWB/DT/B2/02/02	SWB/DT/B4/01DR	SWB/DT/B4/01SC1M5	SWB/DT/B4/01SC1M	SWB/DT/B4/01NC	SWB/DT/B4/01S0	SWB/DT/B4/01S1	C/05072010
Average Weather Condition	Dry &Cloudy / Rainy	Dry / Cloudy	Cloudy / Rainy	Dry / Cloudy	Dry / Cloudy	Dry / Cloudy	Dry &Cloudy / Rainy	Fresh pepper berries from the field
First night	0.84%	4.72%	1.86%	7.30%	5.29%	0.00%	1.55%	
First day	41.06%	46.29%	24.88%	54.67%	55.04%	41.52%	42.35%	
Second night	0.44%	0.45%	0.82%	-0.25%	-4.67%	0.61%	0.75%	
Second day	23.22%	17.33%	29.13%	13.31%	12.77%	20.08%	22.08%	
Third night	0.36%		-0.67%			0.14%	-0.42%	
Third day	5.22%		10.25%			5.25%	4.68%	
fourth night			-0.71%			-0.23%	-1.03%	
fourth day			4.42%			1.33%	0.60%	
fifth night							-2.46%	
fifth day							2.74%	
Final moisture reduction	71.14%	68.79%	69.98%	75.03%	68.43%	68.70%	70.84%	
Drying Duration (hours)	72	43	96	48	48	--	--	
Moisture (%) v/w <wet basis>	8.8	10.40	10.20	8.40	9.20	9.20	19.20	69.81
Volatile oil (%) v/w	3.76	4.24	4.01	6.99	3.96	3.30	7.02	6.55
Piperine (%) w/w	6.01	4.95	5.71	6.38	5.01	4.57	6.96	4.76
Non-Volatile Ether Extract (%) w/w	8.92	4.79	7.44	9.92	5.92	--	9.70	6.77

Physical observations on the dryer operated in both dry and wet morning at dawn are presented in Figures 4.7a to 4.7d. As from Figures 4.7a and 4.7d, only a very thin film of condensation is observed on a dry morning whereas a fogging screen appears on the inner top of the drying chamber. No condensation has been seen on the side window. On the other hand, a cold and wet morning will cause serious condensation at the inner top and both sides of the acrylic windows. It is particularly bad for the case of 0.2m chimney configuration as the internal condensation conditions are the worst compare to the others as shown in Figure 4.8.

Figure 4.7a: Internal condensation condition under a dry morning (2.0m chimney)

Figure 4.7b: Internal condensation condition under a wet morning (0.2m chimney)

Figure 4.7c: Internal condensation condition under continuous rainy days – a view on a wet morning (1.5m chimney)

Figure 4.7d: Internal condensation condition under continuous rainy days – a view on a wet morning (2.0m chimney)

Figure 4.8: The water path showing at the inner side of the acrylic covers caused by the droplets drifted as the cover was opened – a view on a wet morning (0.2m chimney)

From the observation done on the internal drying environment, it was found that at least half a day of sunny weather will allow the concluding of the drying process and it must happen before the final recoveries of the samples. The experiment batches like SWB/DT/B2/02/02 and SWB/DT/B4/01SC1M5 show that it is good to have at least a considerably warm afternoon before they reach the final value of less than thirty-three per cent of its original weight to stop the drying process.

From Table 4.2, natural sun drying experiment on mixed weather condition (SWB/DT/B4/01S1) has been carried out for a total of five consecutive drying days under the open air. Although the required weight has been achieved on the third day evening, but from the physical touch it does not see able to attain the required dryness (soft surface) due to wet days. The experiment continues until the fifth day. In the case, the sample was packed and sent for chemical analysis on the sixth day. As seen from the Table 4.2, an unsatisfactory result was obtained. This has highlighted the need of investing in a solar dryer to avoid such weather that can cause unnecessary loss due to sudden change in drying conditions.

CHAPTER 5: RECOMMENDATION AND CONCLUSION

This chapter puts a review on the studies done on the research for the solar dryer designed and built for small-scale peppercorn production for smallholdings in Sarawak. A conclusion is then made based on the discussions. Further works were recommended to improve the current studies.

5.1 Review on Discussions

Current studies done mainly concentrated on the finding on the possibility in utilizing some simple existing technologies to accommodate effective drying in peppercorn production for smallholdings in tropical rainforest region. Generally, most of the studies had reflected a true condition and contributed positive response to the drying process. Nonetheless, some finding in certain cases are truly unexpected. Following subsections will put a comment on each of the major findings.

From the result presented, shorter chimney favours mass transport in the airspace and results in more even dryings. It works great on bright hot sunny days whilst, long chimney favours maintaining stable temperature profile inside the drying chamber and it works best at days with high solar intermittency. On sunny days, peppercorn can be recovered in two to three days with either configuration but the final quality will differ as there is a difference in drying profile.

In consecutive rainy days, however, long chimney is the only solution at the later stage of the drying cycle. It is believed the long chimney does limits the exchange of air while maintaining the internal flow at the drying tray with the presence of breeze but limited solar space heating.

In addition, pepper berries are seen still experiencing evapotranspiration when it is fresh and half-dried. The observation (Table 4.2) shown that there is a drop in weight over a night in both cases where berries were placed inside the gunny bags and resting on the tray inside the dryer. Although the weight reduction is not very significant compare to the effect under the daylight, it does shown positive contribution to shorter total drying time. The result of the experimental study with short chimney over a night had further explained the phenomena. It suggested that the pepper berries should have been left inside the dryer when it is still fresh regardless of the weather condition. This statement however will still be valid for long chimney configuration if berries have lost its freshness (partially dried peppercorn).

On the other hand, internal condensation occurring in the drying chamber does risk the berries being re-wetted. A cold morning on a sunny day brings less dew effect compared to the dawn on rainy days. Heavy condensation occurs internally at the top cover of the drying chamber. This problem, however, can be resolved by installing a long chimney, which limits the exchange of wet air from the surrounding atmosphere into the drying chamber. A mild condensation at the internal wall has suggested there is a minimal remoistening issue to the berries.

Last but not least, the use of thick plywood and cast acrylic sheet has brought a significant physical load to the overall weight of the dryer. Though, it can still able to be moved over a mild slope and uneven surfaces like over a road hump and soft grass field during rainy days by merely one adult. The replacement of chimney does not see tough as it is lightweight by nature and guided by the pole stand. Nonetheless, its weight can further be reduced by the use of thinner plywood and acrylic sheets with proper supports.

5.2 System Review

The model dryer had shown overall positive results in the actual field test. The peppercorn production can be produced effectively at a better quality compared to the conventional natural sun drying method. Although there are lacking of some physical evidence on the actual happenings in the dryer due to shortfall in experience and the use of tools, the conclusion can still be made based on the field results.

Generally, the model dryer has shown two to four days drying period in the field test under bright sunny and very wet mixed-weather days respectively with tall chimney. The result is very promising compared to the natural sun drying which yield only one positive result on the sunny day. The other had failed after five days of drying. This has concluded a high potential for the model to work under the tropical rainforest climate.

From the experiment study on the model under different weather conditions, it shows that the model has given encouraging results both during the daylight as well as the night time. Although different configurations have to be done on the model to achieve the optimum result, it has demonstrated a positive feedback if following could be implemented:

(1) Need to shuffle the products at least once a day for more balanced drying effect.
(2) Use long chimney at all-time except during bright hot sunny day.
(3) Arrange the dryer in the morning during start-up so that either side of the dryer facing the sun in perpendicular direction. This will enable the full potential of solar gain.

5.2.1 The Economic Value of the Dryer to the Society

The significance of the proposed dryer is its simple built yet can operate well in different weather condition under tropical rainforest climate. It utilises only natural resources like solar radiation and breeze to work and this helps to keep the operation cost low enough to the depreciation of the one-off initial investment. The cost involved may vary according to the requirement of the end user as long as one does meet the basic system configuration as illustrated in Chapter 3.

The market prospect of the proposed dryer can be considered prominent as it has brought the results to the reader that it can guarantee the throughput from every single harvest at a quality better than the conventional sun drying solution under the same weather condition; and it can yield in comparatively shorter period of time. Nonetheless the dryer could not assure an exclusive premium product since it does not required close supervision or extensive cares. However, it let the end users to gain some extra time for their field work and need not to worry about the raw harvest once it was loaded in the proposed dryer.

Furthermore, the proposed dryer shall never be restricted to peppercorn production. It can be use for the drying of other food product since the drying environment is optimised for drying the foodstuff. End users would benefit from it especially during consecutive days of unfavourable weather condition.

5.3 General Comment and Recommendations

In the reviews, the model dryer has shown a promising result with simple operation procedures. It is portable and can accommodate at least seven kilograms of stock at one time (with stem). The operation enables recovery of about thirty per cents of the peppercorn in only two to four days. Changes in local weather condition have become immaterial to the drying condition and this enabled better yield with this one time investment.

The experiment study carried out in this research had utilised some expensive material like stainless steel mesh and thick acrylic sheet. It is intended to create a better environment to reduce the risk of failure in terms of heat transfer issue and hygiene factor, which has seen to be not really necessary in the actual practices. In the case, a cheaper and thinner acrylic sheet and coarser UV stabilised PE material can be considered to reduce the overall weight and cost of the dryer. The issue that really matters is the dryer configuration, though a little performance reduction shall be expected.

For future studies, there is a need to investigate further into the use of the corrugated or rippled metal sheet as the absorber material in the solar collector and solar chimney. Hotter air can encourage better potential in mass exchange under the sunlight. Besides, a counter flow design at the solar collector located underneath the drying tray is worthwhile to investigate in order to improve the tunnel based drying condition between the upstream and downstream side of the tray.

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