© 2017 IJSRSET | Volume 3 | Issue 5 | Print ISSN: 2395-1990 | Online ISSN : 2394-4099
Themed Section: Engineering and Technology

Experimental Study of Direct and Indirect Solar Biomass Dryer

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ABSTRACT

Drying of biomass or agricultural products has been essential in preserving food or conversion into fuel. The traditional method of drying is open drying, which is prone to multiple problems such as contamination, infestations and effect from weather. Solar drying in a closed enclosure can help overcome these issues. This paper discusses the experimental study of direct and indirect solar dryer, in terms of its drying capability, optimal configuration and suitability of usage for different conditions. Four different experiments were conducted, all comparing direct and indirect dryer but with different level of air convection, starting with natural convection, forced convection with one fan, followed by two and three fans. It is found that the level of air flow, the manner of which sunlight is absorbed (direct or indirect) and the position of trays affect the drying rate.

Keywords: *Solar Dryer, Direct Drying, Indirect Drying, Biomass*

I. INTRODUCTION

Food security has been a concern for humankind for a long period of time, due to seasonal weather conditions and crop production. Post-harvest losses, seasonal scarcity of food and agricultural products, in addition, global warming, has been the driving concern worldwide for the development of environmentally friendly solution for preservation [1]. Drying plant or biomass has long been a process to preserve plants, usually for food products or fuel. One of the common techniques is dehydration [2], which is the removal of moisture to longer the life of the product, such as fruits and vegetables. Traditionally, dehydration is achieved by drying in open air [3], resulting in several issues.

The modern method of drying, by burning fossil fuel or other sources of energy, offers stable drying process but at a higher cost. It is estimated that 7 – 15% of energy used in industrialized countries is for foodstuff drying, resulting in high operating cost [4]. This is added by the common inefficient ways of utilizing biomass (especially wood) as a main source of energy [5].

Traditional method of drying, although doesn't require any significant or high cost, is associated with multiple issues such as fungal attacks, infestation of insects, birds and rodents, crop losses, rain and weather effects, to name a few [6]. These problems, including exposure of food product to solar rays, deterioration of nutritional values and other issues stated above can be solved using a closed system [7].

Solar dryers, a closed system, can be generally classifies into a) direct, b) indirect and c) mixed mode, involving circulation of drying air. A direct dryer utilizes solar radiation by letting it pass through a transparent cover, directly hitting the products to be direct. Indirect dryer utilizes solar radiation by heating a separate collector and then supplied to the drying chamber [2]. One main disadvantage of solar drying is the intermittent availability of solar radiation and its absence at night, resulting in inconsistent drying time and quality of final dried product. This main disadvantage resulted in the development of hybrid dryer, which involves external supply of heat. O. Ekechukwu et al have classified solar dryers into passive and active drying systems [8]. Other classification method classifies based on mode of heating (direct or indirect) [9].

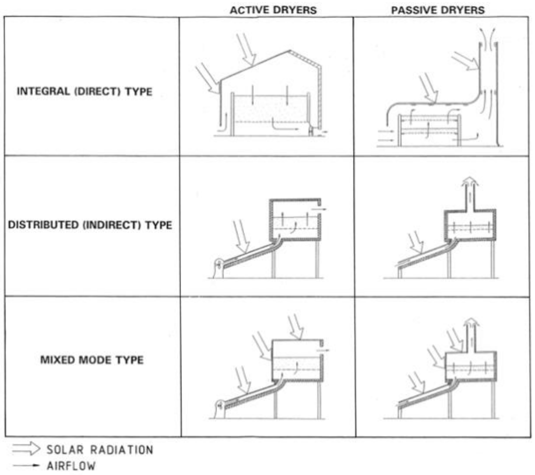

Figure 1: Categorization of solar dryers [8]

The advantage of solar drying when compared to open drying is that they are generally faster, more efficient, hygienic and lower crop losses [10].

This paper presents a comparison of performance between a direct and indirect dryer, using potato slices as the drying sample. Four experiments were conducted, with the first experiment comparing direct and indirect dryer with natural convection and the remaining three experiments comparing both with forced convection at different levels of air flow. Section two of this paper will discuss the methodology, with the following sections presenting the results, discussion and conclusion.

II. METHODOLOGY

Two solar-based dryer was constructed, with one dryer having direct sunlight falling on the mass to be dried, and a second dryer with no direct sunlight coming in contact with the mass to be dried but instead falling onto a collector. The collector will absorb the heat from the sunlight and transferred to the chamber to remove moisture from the mass. The chamber is identically sized to maintain a constant volume. Figure 2 shows the direct dryer on the left and indirect dryer on the right. The dryers are painted black to maximize the heat absorbed.

Figure 2: The front of direct dryer (left) and indirect dryer (right)

Figure 3: The back of direct dryer (left) and indirect dryer (right)

Figure 3 shows the back of the dryers, with exhaust opening. The exhaust opening will be left open without any fan for Experiment 1 (natural convection) and equipped with fan for Experiments 2, 3 and 4 (forced convection) with various numbers of fans. Experiment 2 will investigate forced convection with one fan, Experiment 3 for forced convection with two fans and Experiment 4 for forced convection with three fans.

All experiments were conducted between 11 a.m. to 6.00 p.m. on four different days, with the direct and indirect dryer run simultaneously.

Thermometer was used to measure the ambient temperature and chamber temperature hourly.

Figure 4: Preparation of potato slices samples

Potato was used as samples to test the performance of dryer due to its moisture content. The potatoes were sliced at similar thickness. Figure 4 shows initial weighing of the potatoes, starting at 100g for all experiments. During the experiment, the mass of the potatoes is then weighted hourly to observe the mass reduction.

The potatoes are placed on three different levels in the dryers, which are bottom, middle and top as in Figure 5

Figure 5: Trays inside the dryer

During the hourly weighing of potatoes, all potatoes on three trays are weighed. The hourly ambient and chamber temperature, mass of potatoes for all three trays, for both direct and indirect dryers are then tabulated, compared and analysed.

III. RESULTS AND DISCUSSION

Table 1 shows the ambient temperature recorded for Experiment 1, 2, 3 and 4, which were conducted on four different days. The purpose of this measurement, other than to compare the temperature with the chamber temperature, is to determine if there are extreme differences in temperature throughout the four days.

Table 1: Ambient temperature recorded for all experiments

Time	Temperature			
	Exp. 1	Exp. 2	Exp. 3	Exp. 4
1100	33	36	36	34
1200	36	36	37	36
1300	36	35	37	36
1400	37	36	36	35
1500	36	38	38	36
1600	36	37	37	36
1700	35	36	36	36
1800	35	35	35	35

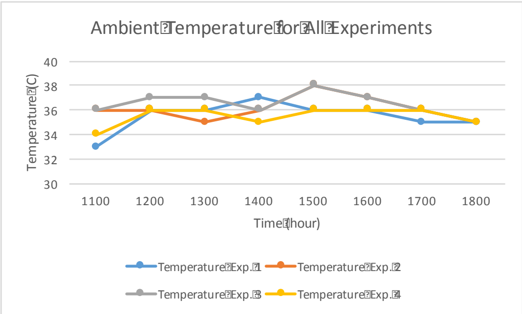

Figure 6: Ambient temperature recorded for all experiments against time

Figure 6 shows that throughout the four days, the temperature hovers around 34^{o}C to 37^{o}C, with one maximum peak at 38^{o}C on Experiment 3 and one low at 33^{o}C on Experiment 1.

A. Experiment 1 – Comparison between Direct and Indirect Dryer with Natural Convection (no fan)

Experiment 1 was conducted to compare the performance between direct and indirect dryer, with no fan or using only natural convection. Table 2 and Table 3 shows the temperature and mass recorded for both dryers from 1100 until 1800.

Table 2: Mass and temperatures recorded for direct dryer (Exp. 1)

Time	Direct Dryer				
	Mass (g)			Temperature (°C)	
	Top Tray	Middle Tray	Bottom Tray	Chamber	Ambient
1100	100	100	100	33	33
1200	85	89	92	45	36
1300	68	74	76	41	36
1400	50	57	62	45	37
1500	41	49	55	42	36
1600	35	42	47	42	36
1700	29	35	38	39	35
1800	26	31	36	37	35

Table 3: Mass and temperatures recorded for indirect dryer (Exp. 1)

Time	Indirect Dryer				
	Mass (g)			Temperature (°C)	
	Top Tray	Middle Tray	Bottom Tray	Chamber	Ambient
1100	99	100	100	33	33
1200	84	95	85	41	36
1300	72	83	74	40	36
1400	58	68	65	41	37
1500	53	60	57	40	36
1600	48	55	53	39	36
1700	41	48	45	36	35
1800	37	44	40	35	35

Table 4: Temperature difference between chamber and ambient for direct and indirect dryer (Exp. 1)

Time	Direct	Indirect
1100	0	0
1200	9	5
1300	5	4
1400	8	4
1500	6	4
1600	6	3
1700	4	1
1800	2	0

Table 4 shows the highest temperature difference between the ambient temperature and chamber occurs in the direct dryer, which is at 9°C, at 12.00 in the afternoon. At similar time, the indirect dryer also records the highest temperature difference, at 5°C, lower than the direct dryer. The direct dryer outperforms the indirect dryer in terms of temperature difference at all points of data measured throughout the experiment.

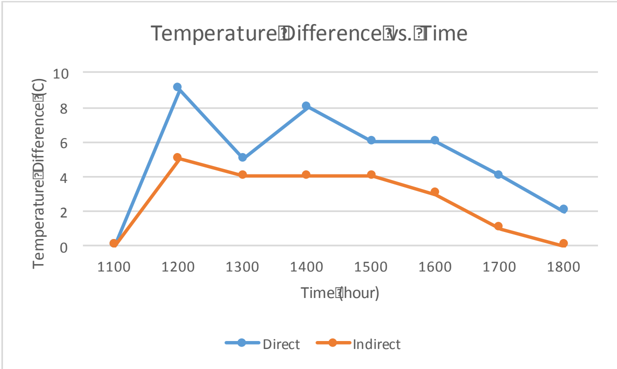

Figure 7: Temperature difference vs. time (Exp. 1)

Figure 7 shows the temperature difference trend between direct and indirect dryer throughout the day. In can be seen in the trends, the direct dryer is more sensitive to the temperature of the ambient, fluctuating more throughout the day, compared to the indirect dryer. This fluctuation might affect the quality of the dried materials but not tested in this study.

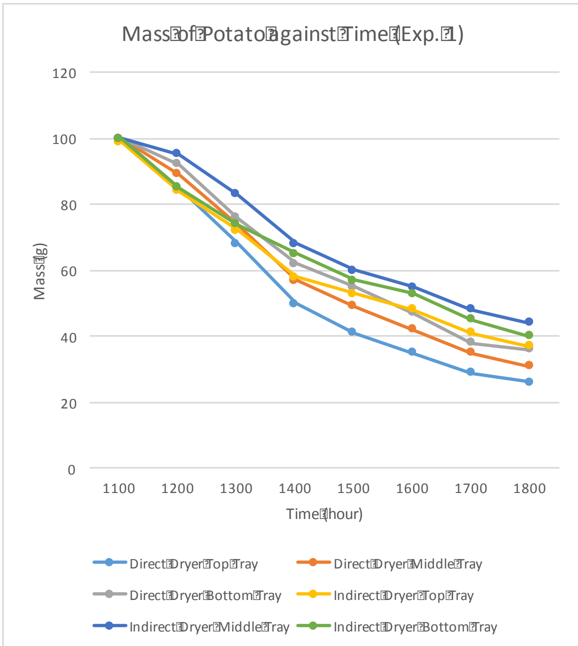

Figure 8: Mass of potatoes against time for all trays (Exp. 1)

Figure 8 shows the mass reduction of potatoes for Experiment 1, for both dryers and all trays. At the end of 6.00 p.m., the top tray of the direct dryer has the lowest mass or highest mass reduction. The middle tray of indirect dryer has the least mass reduction. The bottom and top tray of indirect dryer still outperforms the middle and bottom tray of the direct dryer. In total, the direct dryer removed 216g of mass (moisture) from the potatoes and the indirect dryer removed 188g of mass.

B. Experiment 2 – Comparison between Direct and Indirect Dryer with Forced Convection (one fan)

Experiment 2 was conducted to compare the drying performance of direct and indirect dryer with one fan activated in each dryer to assist the movement of air thus having forced convection. Table 5 and Table 6 shows the temperature and mass recorded for both dryers from 1100 until 1800.

Table 5: Mass and temperatures recorded for direct dryer (Exp. 2)

Time	Direct Dryer				
	Mass(g)			Temperature (^oC)	
	Top Tray	Middle Tray	Bottom Tray	Chamber	Ambient
1100	100	100	101	36	36
1200	82	86	90	38	36
1300	63	71	77	45	35
1400	55	63	68	43	36
1500	48	55	59	44	38
1600	36	39	44	40	37
1700	29	35	38	39	36
1800	25	28	32	39	35

Table 6: Mass and temperatures recorded for indirect dryer (Exp. 2)

Time	Indirect Dryer				
	Mass(g)			Temperature (^oC)	
	Top Tray	Middle Tray	Bottom Tray	Chamber	Ambient
1100	100	101	100	36	36
1200	85	89	88	37	36
1300	72	78	76	38	35
1400	66	71	69	37	36
1500	52	64	62	40	38
1600	44	55	54	37	37
1700	37	48	43	37	36
1800	33	42	38	36	35

Table 7: Temperature difference between chamber and ambient for direct and indirect dryer (Exp. 2)

Time	Direct	Indirect
1100	0	0
1200	2	1
1300	10	3
1400	7	1
1500	6	2
1600	3	0
1700	3	1
1800	4	1

Table 7 shows that the highest temperature difference occurs at 1300 at 10^oC difference for the direct dryer and only 3 for the indirect dryer, making the direct dryer having a 7^oC higher temperature difference than the indirect dryer, compared to 4^oC for Experiment 1. This shows that the one fan forced convection is beneficial to the direct dryer in terms of increasing the temperature of the direct dryer but lowering the temperature of the indirect dryer, in relative to Experiment 1. It is still to be noted that the chamber temperature of the indirect dryer is higher compared to the ambient temperature in 6 out of the 8 hours recorded.

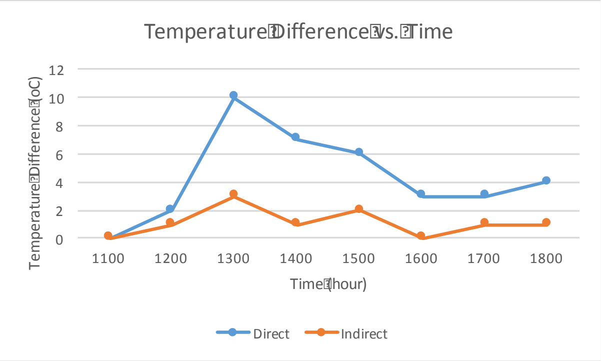

Figure 9: Temperature difference vs. time (Exp. 2)

Figure 9 shows the temperature difference of the chambers of dryers and the ambient temperature. It can be seen that the peak temperature difference occurs at 1300 for both dryers. The peak of the dryer direct is significantly high compared to the indirect dryer, which hovers around 0 to 3^oC of difference. For direct dryer, the temperature difference continued to drop until 1700 to 3^oC, before rising slightly at 1800.

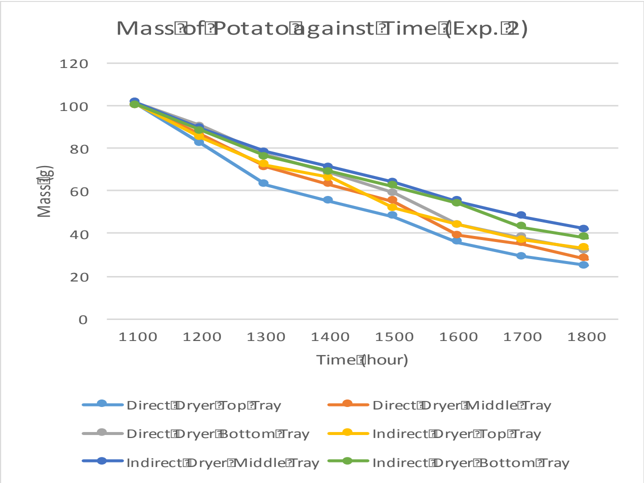

Figure 10: Mass of potatoes against time for all trays (Exp. 2)

In terms of drying performance, the top tray of direct dryer still performs the best, similar to Experiment 1 and the middle tray of indirect dryer still has the lowest mass reduction. The order of mass reduction is similar to Experiment 1. The total mass reduction for direct dryer is 216g and 188g for the indirect dryer.

C. Experiment 3 – Comparison between Direct and Indirect Dryer with Forced Convection (two fans)

Experiment 3 was conducted to compare the drying performance of direct and indirect dryer with two fans activated in each dryer to assist the movement of air thus having forced convection. Table 8 and Table 9 shows the temperature and mass recorded for both dryers from 1100 until 1800.

Table 8: Mass and temperatures recorded for direct dryer (Exp. 3)

Time	Direct Dryer				
	Mass (g)			Temperature (^{o}C)	
	Top Tray	Middle Tray	Bottom Tray	Chamber	Ambient
1100	99	100	100	36	36
1200	72	76	81	49	37
1300	41	50	56	66	37
1400	27	32	39	46	36
1500	22	23	29	52	38
1600	18	20	26	48	37
1700	14	17	22	42	36
1800	10	14	19	39	35

Table 9: Mass and temperatures recorded for indirect dryer (Exp. 3)

Time	Indirect Dryer				
	Mass (g)			Temperature (^{o}C)	
	Top Tray	Middle Tray	Bottom Tray	Chamber	Ambient
1100	99	101	99	36	36
1200	76	85	83	38	37
1300	56	65	64	44	37
1400	40	48	46	40	36
1500	24	37	36	40	38
1600	20	28	26	39	37
1700	18	25	22	37	36
1800	16	21	18	36	35

Table 10: Temperature difference between chamber and ambient for direct and indirect dryer (Exp. 3)

Time	Direct	Indirect
1100	0	0
1200	12	1
1300	29	7
1400	10	4
1500	14	2
1600	11	2
1700	6	1
1800	4	1

Table 10 shows the temperature difference between the chamber and the ambient. The temperature difference significantly increased in Experiment 3, reaching up to 29ºC of difference in the direct dryer and 7ºC in the indirect dryer, both high occurring at 1300. This translates into significant assistance of the fans in helping to increase the temperature of the chamber.

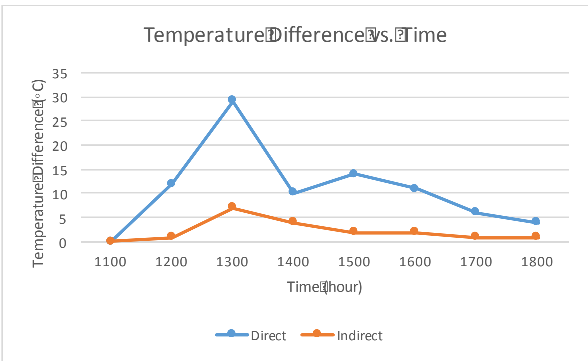

Figure 11: Temperature difference vs. time (Exp. 3)

Figure 11 shows the temperature difference of the chambers of dryers and the ambient temperature. Again, it can be seen that the peak temperature difference occurs at 1300 for both dryers. The peak of the dryer direct is significantly high compared to the indirect dryer, which hovers around 0 to 29°C of difference. The indirect dryer shows a similar trend with the previous experiments, with no extreme peaks, hovering between 0 to 7°C of temperature difference.

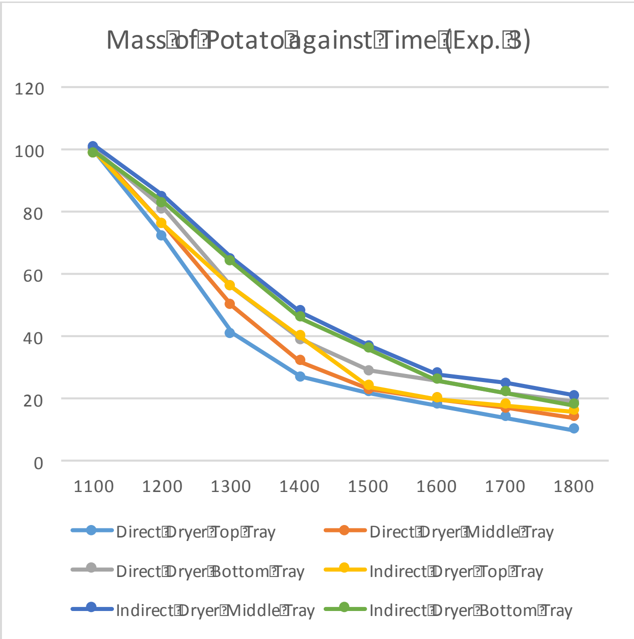

Figure 12: Mass of potatoes against time for all trays (Exp. 3)

As for the drying performance, the top tray of direct dryer still performs the best and the middle tray of indirect dryer still has the lowest mass reduction. However, the bottom tray of direct dryer slightly outperforms the top tray of indirect dryer in this experiment. The total mass reduction for direct dryer was 256g and 244g for indirect dryer. The mass reduction for indirect dryer for Experiment 3 outperforms direct dryers for both Experiment 1 and 2.

D. Experiment 4 – Comparison between Direct and Indirect Dryer with Forced Convection (three fans)

In Experiment 4, the number of fans were increased to three for each dryer, to study if the increasing number of fans will benefit the drying performance. Table 11 and Table 12 shows the temperature and mass recorded for both dryers from 1100 until 1800.

Table 11: Mass and temperatures recorded for direct dryer (Exp. 4)

Time	Direct Dryer				
	Mass(g)			Temperature (°C)	
	Top Tray	Middle Tray	Bottom Tray	Chamber	Ambient
1100	101	100	100	34	36
1200	77	80	85	56	36
1300	52	62	69	65	35
1400	35	44	54	64	36
1500	26	33	35	37	38
1600	22	23	25	49	37
1700	18	20	23	42	36
1800	15	16	19	40	35

Table 12: Mass and temperatures recorded for indirect dryer (Exp. 4)

Time	Indirect Dryer				
	Mass(g)			Temperature (°C)	
	Top Tray	Middle Tray	Bottom Tray	Chamber	Ambient
1100	99	100	100	34	34
1200	83	87	85	38	36
1300	66	71	67	40	36
1400	52	57	53	42	35
1500	35	50	41	43	36
1600	25	38	36	38	36
1700	23	33	30	37	36
1800	20	28	26	37	35

Table 13: Temperature difference between chamber and ambient for direct and indirect dryer (Exp. 4)

Time	Direct	Indirect
1100	-2	0
1200	20	2
1300	30	4
1400	28	7
1500	-1	7
1600	12	2
1700	6	1
1800	5	2

Table 13 shows the temperature difference between the chamber and ambient temperature. For direct dryer, the existence of two fans cooled down the chamber at 1100 and 1500. Other than that, the temperature difference remained high, peaking to 30°C difference at 1300. As for indirect dryer, the temperature difference peaked at 1400 and 1500.

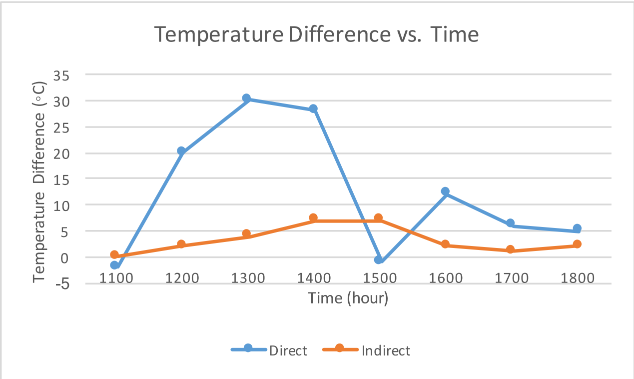

Figure 13: Temperature difference vs. time (Exp. 4)

Figure 13 shows the temperature difference against time. Similar to all three experiments, direct dryer shows significant temperature difference with a large range between 0 to 30ºC. As for the indirect dryer, the temperature difference shows a similar trend compared to the previous experiments, having a relatively small range of difference between 0 to 7ºC.

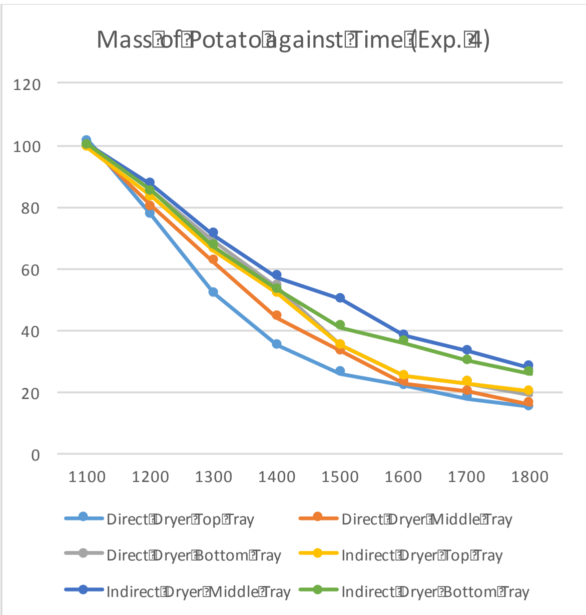

Figure 14: Mass of potatoes against time for all trays (Exp. 4)

Similar rank is again shown for mass reduction, with the top tray of direct dryer having the highest mass reduction and the middle tray of indirect dryer having the lowest mass reduction. The total mass reduction for direct dryer is 240g and 225g for indirect dryer.

Overall Result Comparison

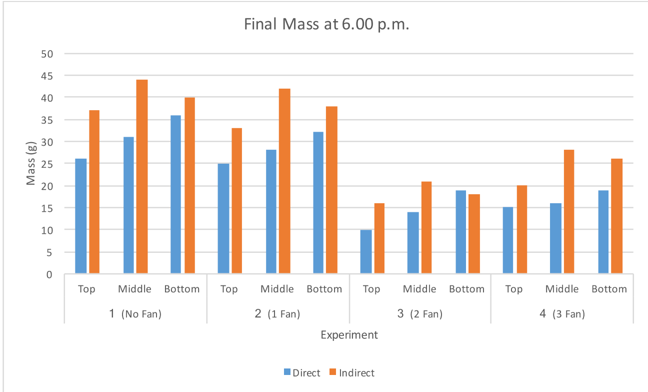

Figure 15: Final mass of potatoes at 1800 for all trays for all experiments

Figure 15 shows the overall comparison of final mass for all four experiments, for all trays. For all experiments, direct dryer has higher mass reduction compared to indirect dryer, except for Experiment 3, where the bottom tray of the indirect dryer outperforms the bottom tray of the direct dryer. Experiment 3, with two fans have the highest mass reduction and Experiment 1 has the lowest mass reduction.

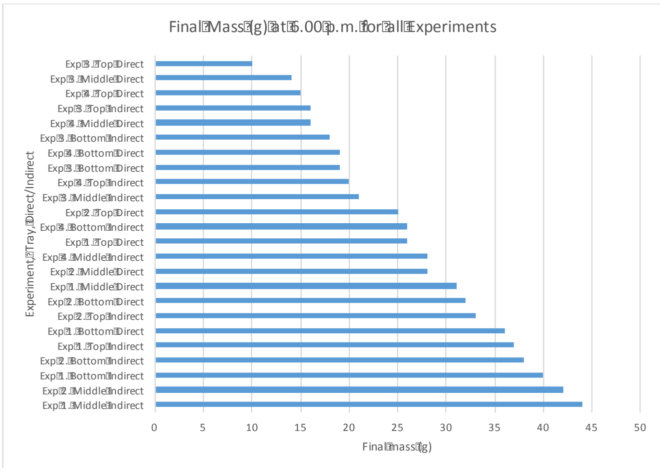

Figure 16: Final potato mass for all trays and all experiments (ranked)

Figure 16 shows the mass reduction for all trays, ranked from the lowest final mass at the top (highest mass reduction) to the lowest mass reduction at the bottom. The best performance of mass reduction is the top tray of direct dryer with two fans, followed by the middle tray of direct dryer with two fans and the top tray of direct dryer with three fans. The best performing for indirect dryer is the top tray with two fans. Although the direct dryer has the best drying performance, different types of applications might favour the indirect dryer to avoid direct contact with sunlight. The middle and bottom trays of indirect dryer has the lowest mass reduction. It can also be seen that having two fans give the optimum mass reduction and adding more fans doesn’t necessarily means better performance. Higher temperature difference do help the drying process most of the time.

IV.CONCLUSION

Two different dryers, direct and indirect dryers were tested for removing moisture from samples of potatoes. Direct dryers perform the best for drying, with having two fans being the optimum. Indirect dryer top tray is ranked at fourth for mass reduction, outperforming other 9 configurations of direct dryer and 11 configurations of indirect dryer. The highest total amount of mass reduction in the same chamber occurs for direct dryer with two fans at 256g and the lowest total amount of mass reduction in the same chamber occurs for indirect dryer with no fan and indirect dryer with one fan, both at 188g. Adding number of fans do help in some cases, for example the top tray of direct dryer with three fans outperforms the bottom tray of direct dryer with two fans. Although direct dryer performs better for drying, each dryer has their own merits, depending on the requirement of application, for example direct contact or indirect contact with sunlight. Both dryers solve the issues with open drying, which are affected by wind, rain and pests.

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