American Journal of Energy Research, 2017, Vol. 5, No. 1, 12-22
Available online at http://pubs.sciepub.com/ajer/5/1/2

DOI:10.12691/ajer-5-1-2

Air-flow Distribution Study and Performance Analysis of a Natural Convection Solar Dryer

Nicholas Musembi Maundu[1,*], Kosgei Sam Kiptoo[1], Kiprop Eliud[1], Dickson Kindole[1], Yuichi Nakajo[2]

[1]Graduate school of engineering, Ashikaga Institute of Technology, Japan, 268-1 Omae, Ashikaga Tochigi, 326-8558, Japan
[2]Division of Renewable Energy and Environment, Ashikaga Institute of Technology, 268-1 Omae, Ashikaga Tochigi, 326-8558, Japan
*Corresponding author: nickmaundu2014@gmail.com, ymnakajo@yahoo.co.jp

Abstract In this research work, an indirect natural convection flow updraft solar dryer was studied with objectives to; study air-flow distribution using Particle Image Velocimetry (PIV) technique, analyze relative humidity and humidity ratio variations in relation to temperature, visualize temperature distribution on drying surface and carry out performance analysis of solar dryer. An already existing dryer was modified in order to suit PIV study experiments. The dryer consisted mainly of; hinged flexible angled solar collector, drying chamber consisting of three drying trays and updraft chimney with metallic absorber. The smoke was introduced, by use of an electronic smoker for visualization of distribution of airflow in the drying chamber, and recorded via high speed camera of 30 fps for the purpose of analysis by use of PIV software. Thermal vision camera was used to capture temperature variation images which indicated highest variance of 1.4°C from the mean of the four line sections. For the general performance analysis, experiments were carried out by drying 2.5 mm sliced apples. Temperature and relative humidity of the airflow were taken at the collector inlet, drying chamber inlet and drying chamber outlet using data loggers. Airflow inlet to solar collector and from drying chamber were determined using hot wire anemometers, irradiance (W/m^2) was measured using radiation meter. PIV results were achieved indicating fair airflow distribution across the drying bed with high correlation coefficient average at around 0.9 and low velocity standard deviation of below 0.004 in a frame across the sections. Imagery results for Turbulent Kinetic Energy indicated an average of 4.0 x 10-5 m^2/s^2 which implied a fairly smooth airflow which can be said to be a characteristic of natural convection updraft solar dryer. Experiments conducted on loaded solar dryer showed high uniformity on the dried product across the trays; thus, an indication of good airflow distribution across the drying trays corresponding to PIV results obtained. Fresh apples of moisture content 86% (wet basis) were dried to moisture content of 13.74% (wet basis) within 8 hours 40 minutes; the dryer achieved overall efficiency of 16.49 % at an average horizontal irradiance of 525.29 W/m^2. The dried apples were found to have good texture, color and taste.

Keywords: *PIV technique, humidity ratio, performance analysis*

Cite This Article: Nicholas Musembi Maundu, Kosgei Sam Kiptoo, Kiprop Eliud, Dickson Kindole, and Yuichi Nakajo, "Air-flow Distribution Study and Performance Analysis of a Natural Convection Solar Dryer." *American Journal of Energy Research*, vol. 5, no. 1 (2017): 12-22. doi: 10.12691/ajer-5-1-2.

1. Introduction

Concerns over climate change and food security are among the current major challenges in global perspective. The need to minimize utilization of fossil fuels as a mitigation measure in curbing the extent of greenhouse gas emissions has brought about extensive research on renewable energy applications. Renewable energy does not only contribute to a better environment but also give a strong boost to economy through job opportunities as well as improving food security through preservation systems such as solar dryers.

Post-harvest losses have been a challenge to farmers for many years, they have deprived farmers the much needed returns from the farm output and brought down the potential of agricultural contribution to economy. Post harvesting losses are estimated at 30%-40% of the farm produce and may heighten to 80% under adverse conditions such as bumper harvest period [1]. Solar drying is considered a traditional method and has been used by many farmers in developing and developed countries for many years as a food preservation method, traditionally, sun drying as the leading method of food drying. Solar dryers make use of a closed space which accommodates the product being dried, this gives better and hygienic results. Basically, there are three types of solar dryers namely; direct solar dryers, indirect solar dryers, and mixed solar dryers. Description, mode of operation, merits and demerits of each of the dryers have been discussed by *A. A. Elbaii and S. M Shalaby*, 2012 [2].

Drying process involves vaporizing water (moisture content) in the product, the latent heat of vaporization must be supplied to increase vapor pressure over the product. During this process, airflow is required to remove vapor away from the product [3]. In indirect solar dryers, the latent heat of vaporization is supplied to drying chamber from the solar collector, the solar collector absorbs the solar energy raising the temperature of the air within the collector while lowering its relative humidity. The hot air then flows by convection through the drying chamber and exit through the chimney by thermo-siphoning effect. Distribution of the air flow across the drying chamber is key in determining the efficiency and uniformity of the dried product.

Most solar dryers make use of the tray systems in the drying chamber making trays an important part of the drying bed. Tray dryers are widely used in a variety of applications because of their simple design and capability to dry products at high volume. The greatest drawback of the tray dryer is uneven drying because of poor airflow distribution in the drying chamber. By understanding the airflow distribution analysis methodology, suitable design approach may be used to improve tray dryer performance, increase quality of dried product and produce uniform drying [4].

A lot of emphasis has been placed on thermal performance analyses with most research being devoid of the effect of airflow distribution in the drying chamber to the quality and the overall efficiency of the drying system. In this work, in addition to thermal performance of indirect solar dryer, airflow distribution across drying chamber has been studied by use of PIV technique. PIV is an effective tool in visual analysis of air flow distribution. In addition to visualization of the air flow distribution across the drying chamber, other parameters such as velocity and turbulent kinetic energy are also analyzable. Unlike computational fluid dynamics (CFD) whose prediction of air flows is based on mathematical modeling and computer simulations in a virtual flow laboratory, PIV technique provides real experimental airflow analysis whose results can easily be translated and understood by solar dryer enthusiast with little or no background knowledge on fluid dynamics. PIV provides quantitative and qualitative description flow phenomena of air using measurements as opposed to quantitative prediction flow phenomena provided by CFD software thus making it a suitable tool for laboratory scale models.

2. Materials and Methods

The authors used an already designed and existing solar dryer, the drying chamber was modified to suit PIV study with most of the other parts of the solar dryer system remaining as per original design. The materials used for this dryer are listed in table as shown in appendix C. The solar dryer collector area was 0.56265m^2 and has an inlet of 0.00925m^2.

2.1. Modification of the Existing Solar Dryer - Drying Chamber

This is the only part of the dryer which was modified from the existing natural convection solar dryer. The drying chamber was dimensioned to be 52 cm long , 50 cm wide and 69 cm high. The top, bottom and front were constructed using 1.3 cm thick plywood. The door has been provided at the rear end with hinges and wooden locks. It is constructed using 1.3 cm thick plywood, the edges being lined with rubber seals to enable tight-fitting for better thermal insulation.

The two opposite sides (i.e. right and left) of drying chamber were constructed using transparent PVC material of 1mm thickness and its outer edges reinforced using 4 mm thickness plywood.

Three removable trays of dimensions 47cm by 47 cm were constructed using wire mesh with their four outer edges reinforced using plywood. The slide bars for holding the trays were fixed at distances of 20 cm, 36 cm and 53 cm from the bottom of the chamber.

Hot air enters the drying chamber through inlet at the bottom front and leaves through the chimney at the top back face.

Figure 1 and Figure 2 show the initial design and the modified solar dryer respectively

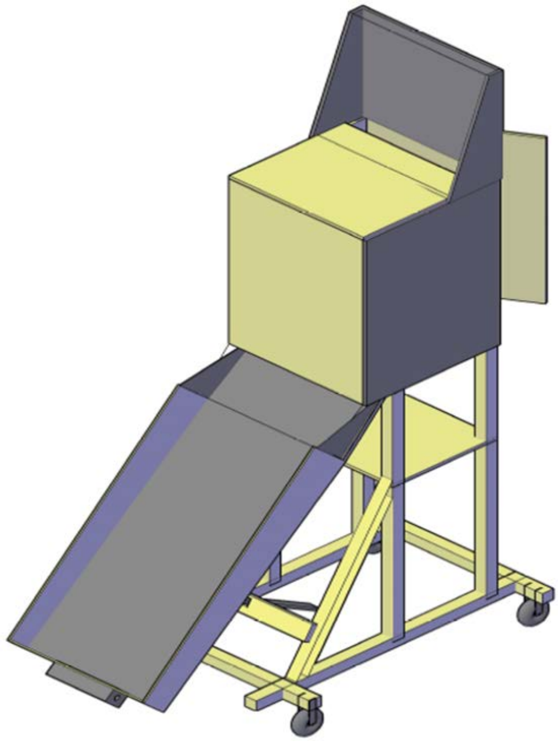


Figure 1. Existing solar dryer design

2.2. Basic Performance Analysis Equations

The amount of moisture to be removed from the product, m_o, is determined as [5];

$$m_o = m_w \frac{\left(M_i - M_f\right)}{\left(100 - M_f\right)} \quad (1)$$

Where; m_o= the amount of moisture to be removed from the product, m_w = initial mass of product to be dried, M_i = the initial moisture content in % wet basis and M_f =the final moisture content % wet basis.

The quantity of heat required to evaporate water is determined as shown in eqn.(2);

$$\mathbb{Q} = m_o x h_{fg} \quad (2)$$

where Q = the amount of energy required for the drying process in kJ, h_{fg}= latent heat of vaporization in kJ/kg of water.

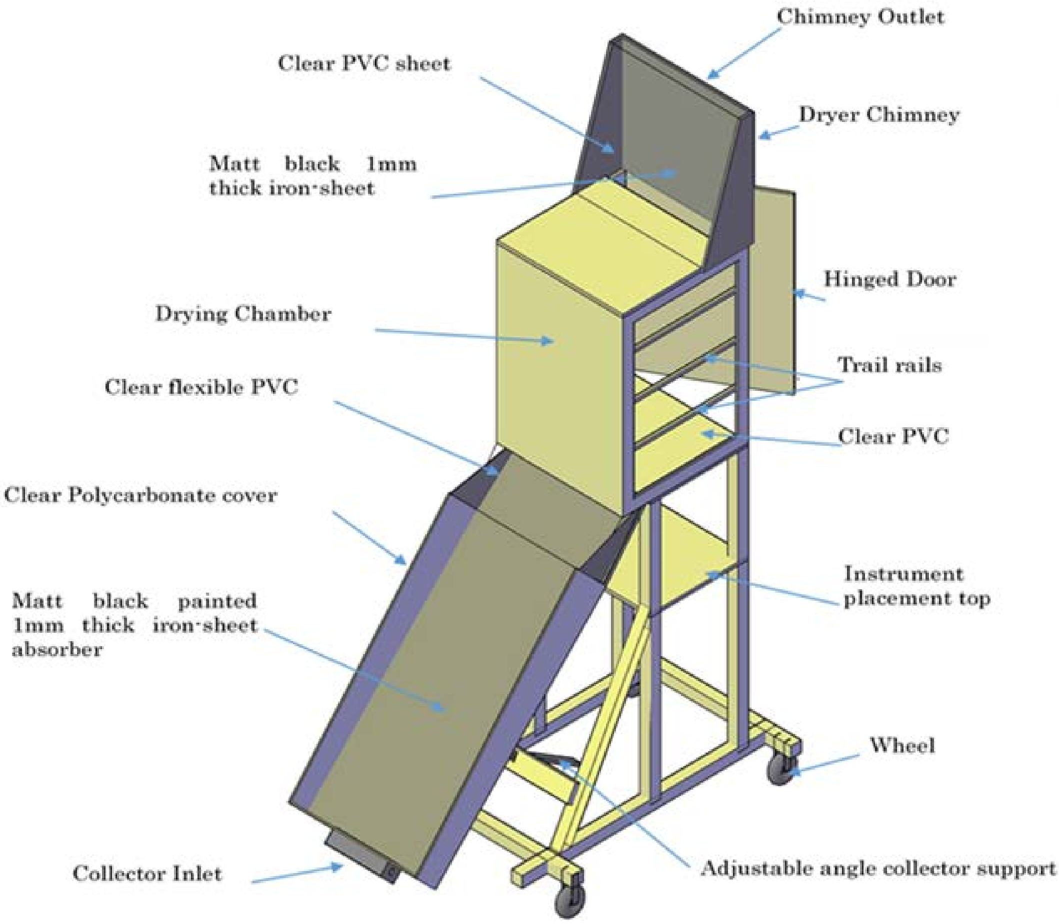


Figure 2. Modified Design solar dryer for PIV study

The latent heat of vaporization (h_{fg}) can be determined using equation given by *Youcef-Ali et al (2002)* [6];

$$h_{fg} = 4.186\times10^{3}\left(597-0.56\times T_p\right) \tag{3}$$

T_p is the temperature of the product being dried in °C, in this case, average temperature was considered. The total heat energy in kJ required to evaporate water in ideal situation can be determined from eqn.(4) [6,7];

$$E = m_a(h_f - h_i)t_d = \frac{A_C I\eta}{1000} \tag{4}$$

where m_a is the mass flow rate of air in kg/hr, h_f and h_i are final and initial enthalpy of drying air in kJ/kg of air and *I* is the global radiation on the horizontal surface during the drying period (kJ/m^2).

Where I_T is the rate of radiation incidence on the absorber surface (W/m^2) and thus the total radiation incident to the total area of the collector, IA_{ct} can be written as:

$$IA_{ct} = \tau I_T A_c \tag{5}$$

The reflected energy from the absorber $\mathbb{Q}_\rho$ is given as;

$$\mathbb{Q}_\rho = \rho\tau I_T A_c \tag{6}$$

Where ρ is reflection coefficient of the absorber and τ transmittance of the cover.

The drying rate is proportional to the difference in the moisture content between materials to be dried and the equilibrium moisture content. Average drying rate A_{dr} can be determined from the mass of moisture removed by solar heat and drying time (t_d) by the equation shown below;

$$A_{dr} = \frac{m_o}{t_d} \tag{7}$$

Where A_{dr} is the average drying rate, kg/hr.

The percentage moisture removed from the product γ% and the percentage final moisture content of the dried material can be determined from equations 8 and 9 respectively [8];

$$\gamma\% = \frac{m_w - m_d}{m}\times100 \tag{8}$$

Where m_d is the final mass of the dried product in kg, the percentage final moisture (m_f) content;

$$m_f = \frac{100-\gamma}{100} m_w. \tag{9}$$

The total collected solar Energy falling on the collecter (E_T) can be obtaineded as;

$$E_T = A_c I. \tag{10}$$

Efficiency of solar dryer in relation to total heat energy for evaporation and irradiation relates as [8];

$$\eta = \frac{E}{A_c I} \tag{11}$$

Where E is the total useful energy received by the drying air in kJ as obtained from egn. (4). The energy falling on the collector from the sun can be converted to units of energy (E_u), (kWh) as;

$$E_u = \frac{A_c I}{3.6 \times 10^6}. \quad (12)$$

Air pressure across the drying product bed can be determined by the equation given by *Jindal and Gunasekaran (1982);*

$$P = 0.00308 g (T_i - T_{am}) H \quad (13)$$

Where H is the pressure head (height of the hot air column from the base of the dryer to the point of air discharge from the dryer), P is the air pressure in Pascals, g is acceleration due to gravity and T_{am} is the ambient temperature (°C).

3. Experiment Set-up

The experiment was carried out in two stages, under no load condition and under load condition. Camera recorder was used to record high speed videos so as to be used in PIV Flownizer Software for airflow analyses. The recording speed of the camera used was 30 frames per second. The experiment set-up for no load condition was as shown on Figure 3. Under load condition, the same solar dryer was used for normal drying of sliced apples to moisture content acceptable for packaging and storage. This phase did not require Electronic smoker, video recorder or the blue back ground.

3.1. Stage I: No Load Condition

Under this condition, the dryer was run under no load . The dryer was placed outside in the sun in order for the airflow condition to stabilize before the experiment was carried out. For the airflow to actualize, the collector absorber and chimney absorber collects solar irradiance thus raising air temperature and facilitating the airflow through the drying chamber by thermo-siphoning effect. The smoke was introduced through the solar collector inlet. The sides of interest were the two opposite transparent sides of drying chamber. On one of these sides, blue background was created using a blue Styrofoam sheet placed 60 cm from drying chamber, while on the opposite side, high speed camera was set for recording videos. The side with the camera recorder was covered with black clothing in order to provide clarity of the videos being recorded and minimize reflection.

3.2. Stage II: Under Load Condition

Red apples were cut into slices of 2.5 mm, weighed using digital weighing scale, spread evenly on the trays and placed in drying chamber. Humidity and temperature data loggers were set at collector inlet, drying chamber inlet and drying chamber outlet for recording both humidity and temperature at the respective points as shown in Appendix A with recording intervals of 20 minutes.

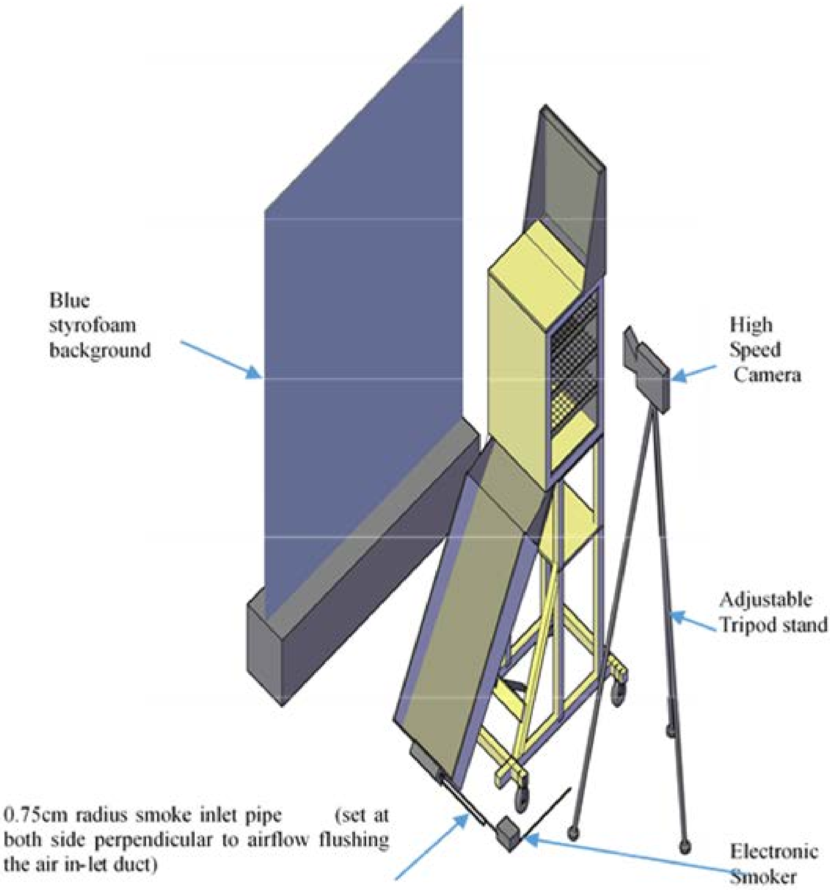


Figure 3. Experimental Set-Up

Thermal imaging camera was used in this phase to give an image of representative temperature distribution within the drying chamber.

This experiment was used to dry the product to moisture content (below M.C of 15%) acceptable for packaging and storage. These results were used for the output performance analysis.

4. Results

The results obtained were categorized into, PIV airflow distribution results and dryer performance results.

PIV Technique Results of Airflow Distribution.

The experiments were carried out on empty trays, the videos obtained were used to carry out particle image velocimetric measurements.

The results here are for airflow of a section approximately 4 cm above the drying chamber inlet and 2 cm just below the 3rd tray. It was difficult to capture video for the whole drying section at once. Some of the results obtained are as shown from Figure 4 to Figure 8.

Loaded tray/Dryer Performance Results

For the performance analysis, sliced fresh apples were dried for 8 hours 40 minutes. Some of the results obtained are graphically represented here. Thermal imaging camera results obtained during this session were as shown in Figure 11.

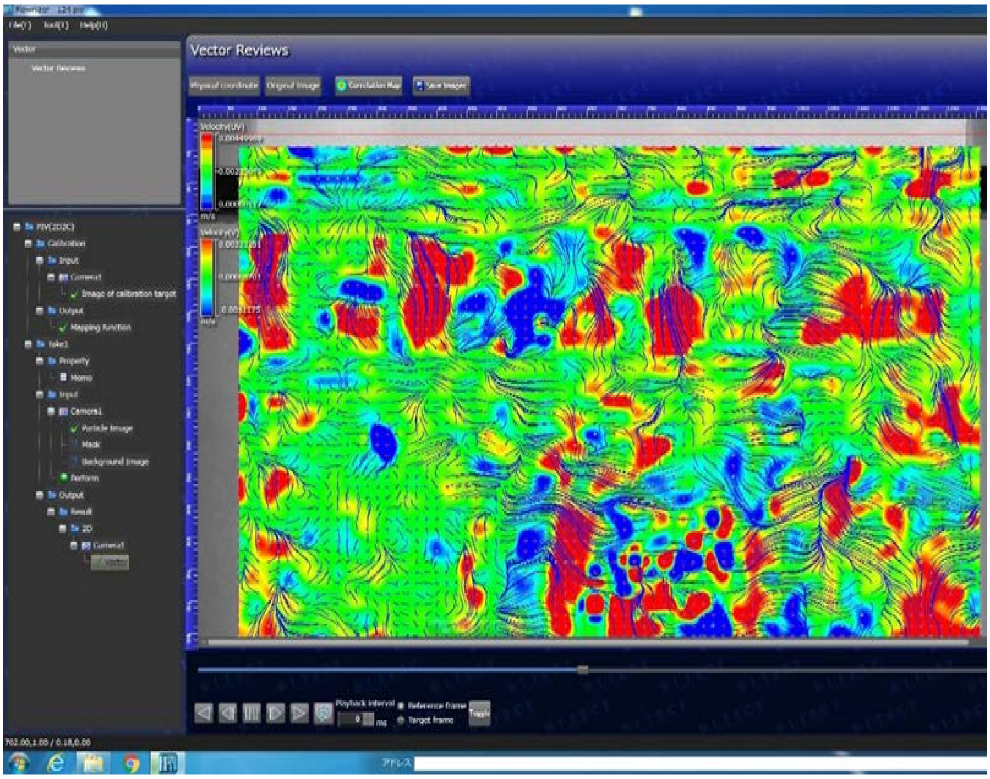


Figure 4. Velocity across the chamber

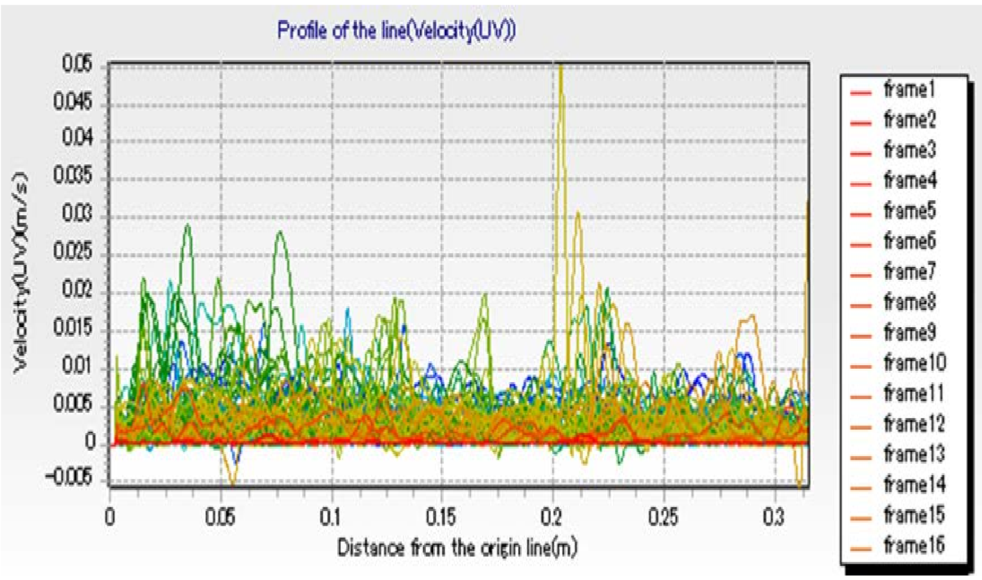


Figure 5. Profile of line velocity(UV) across mid-section

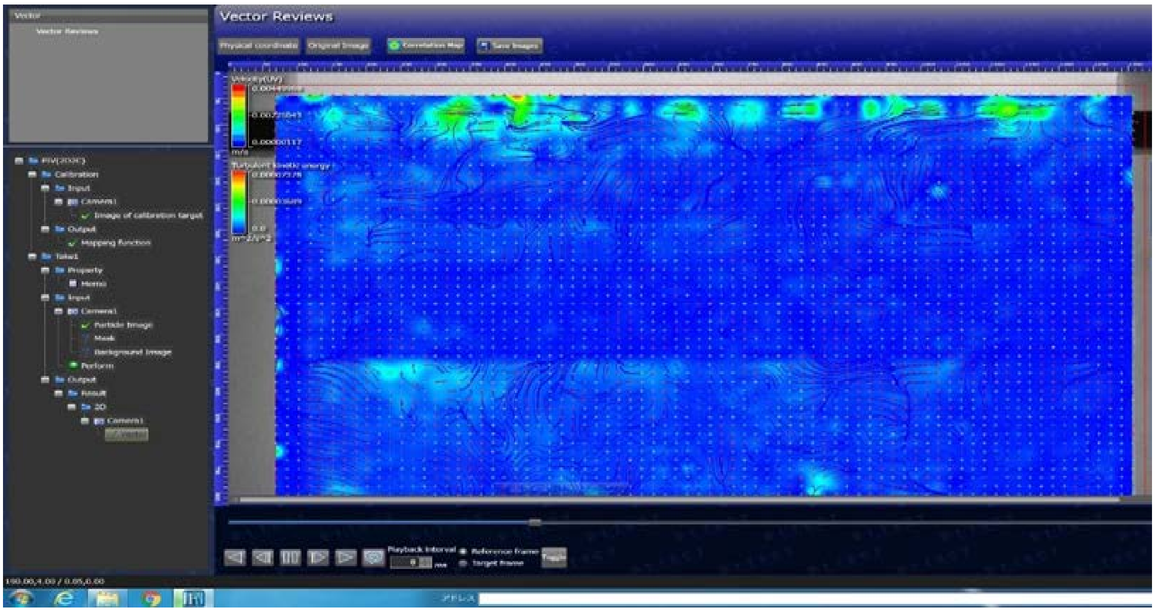


Figure 6. Turbulent Kinetic Energy (TKE)

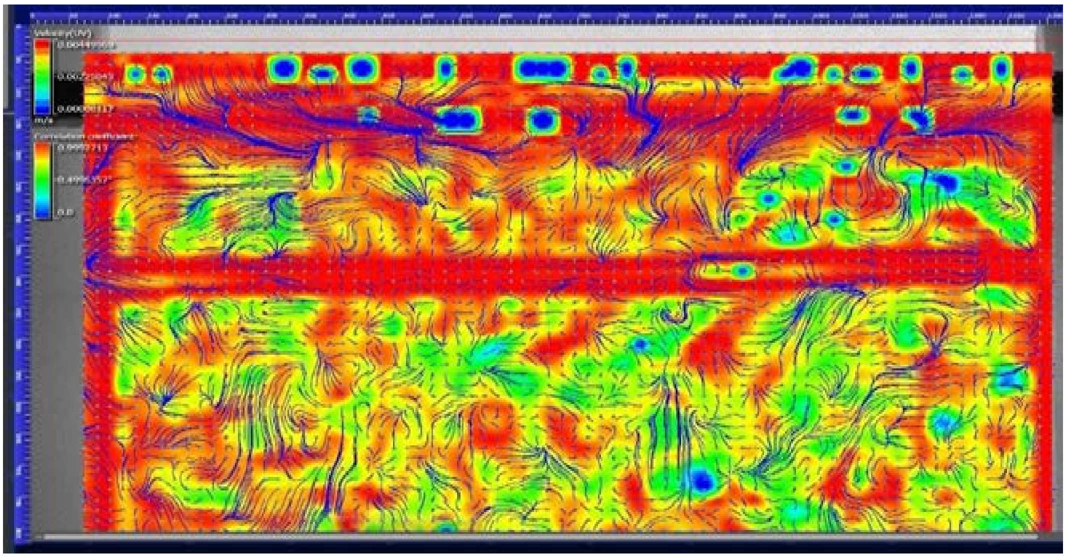


Figure 7. Correlation coefficient (region between the lower tray and upper tray)

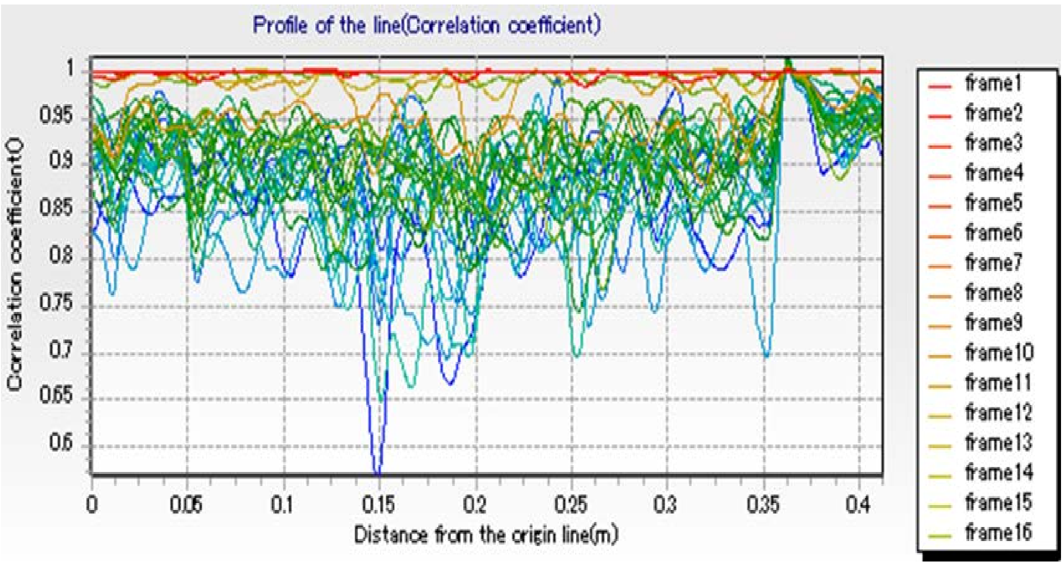


Figure 8. Graph of Correlation Coefficient across the drying chamber

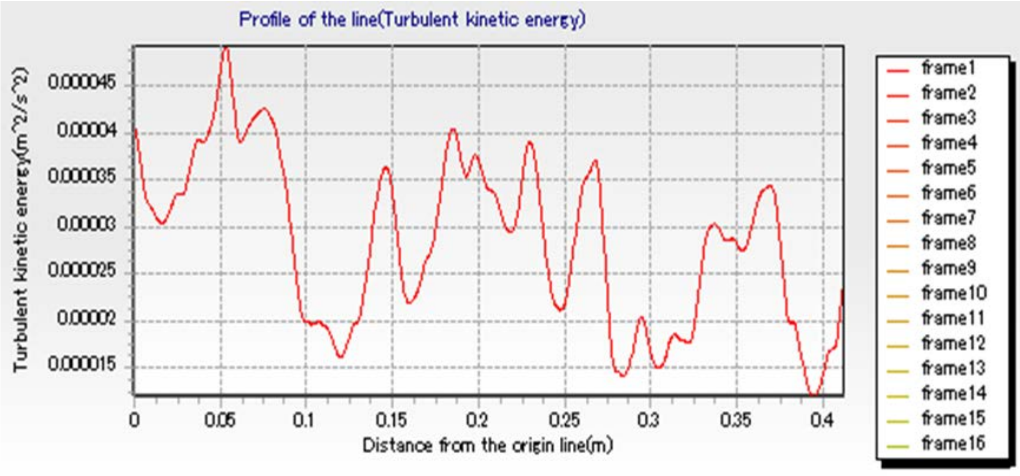


Figure 9. Graph of Turbulent Kinetic Energy across the section (between tray 2 and 3)

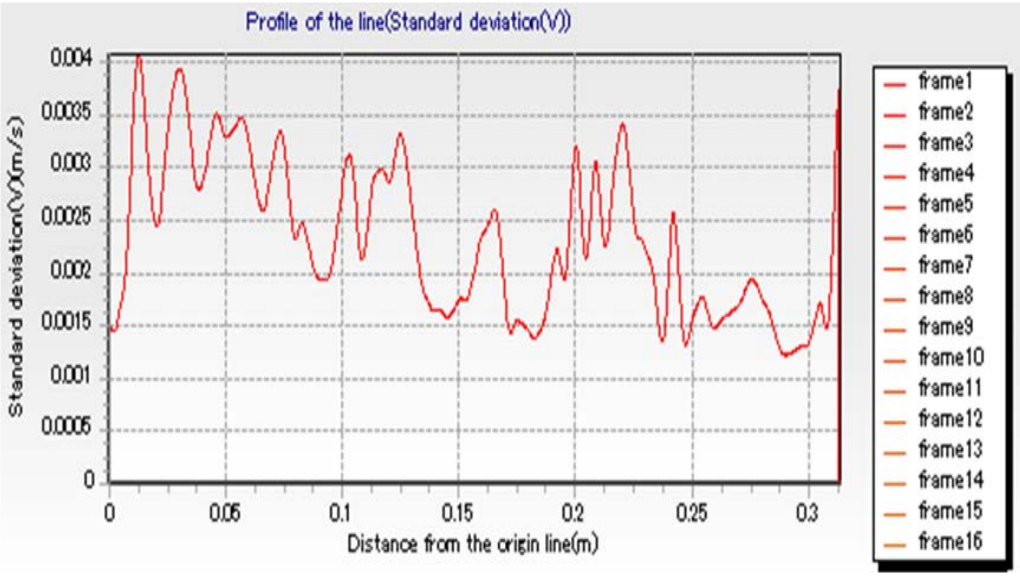


Figure 10. Graph of standard deviation of velocity within frames across the section

Measurements (°C)

Line 1	Max	50.9
	Min	43.9
	Average	44.9
Line 2	Max	49.6
	Min	43.2
	Average	44.2
Line 3	Max	48.2
	Min	42.8
	Average	43.5
Line 4	Max	46.1
	Min	43.6
	Average	44.2

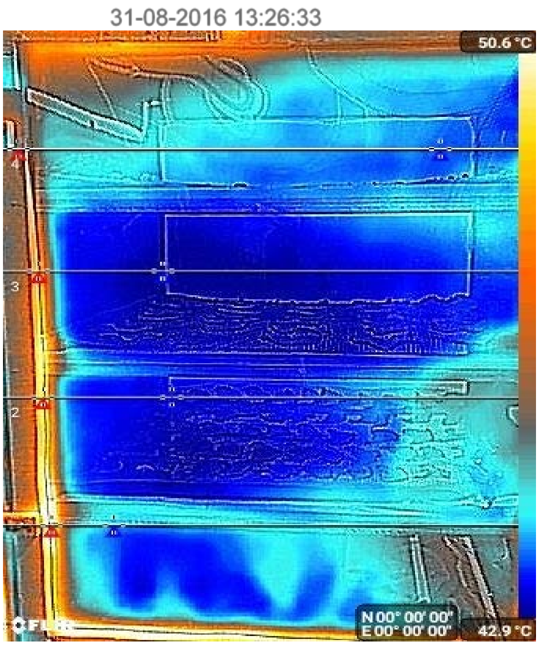


Figure 11. Thermal image showing temperature variations across 4 different sections

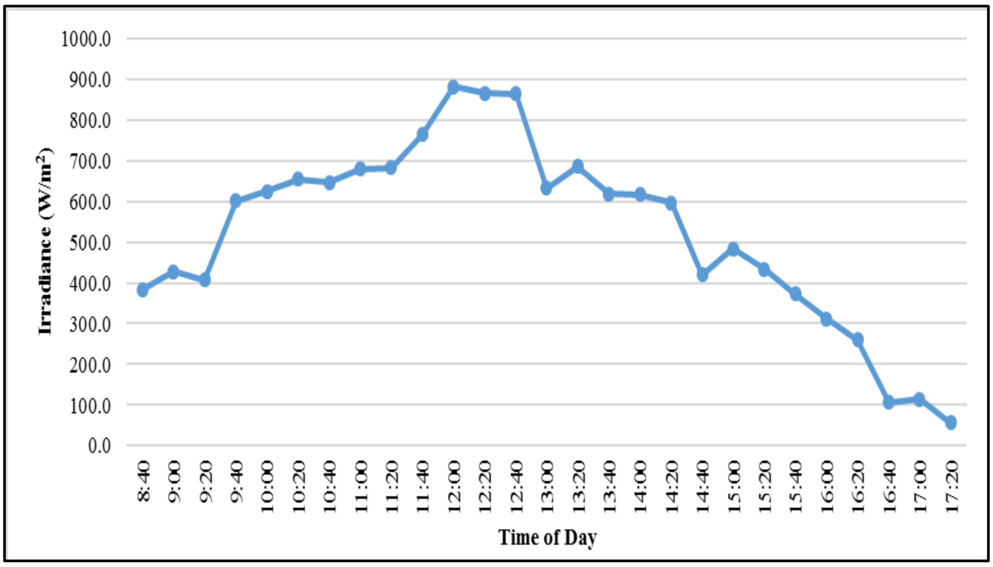


Figure 12. A graph of Irradiance (W/m^2) against time of drying

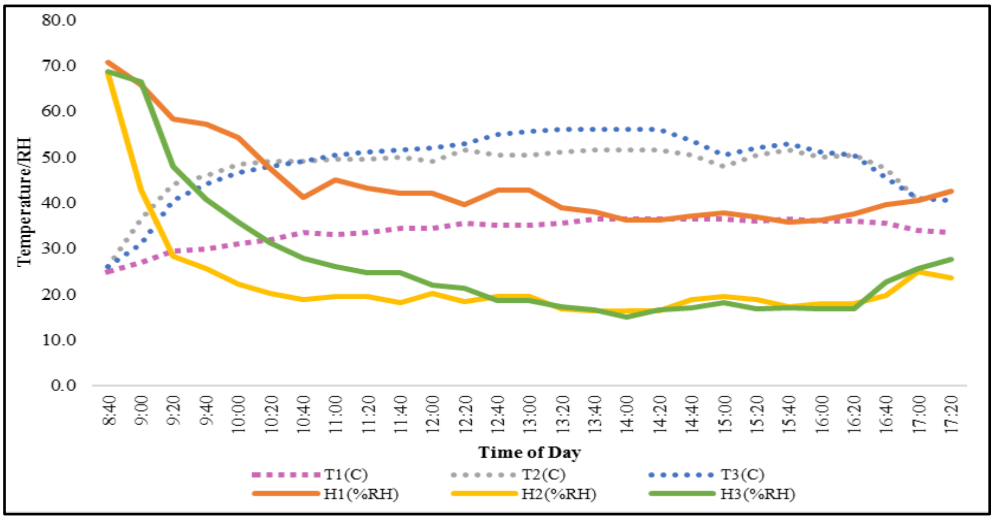


Figure 13. A graph of Temperature and Relative humidity against time of drying

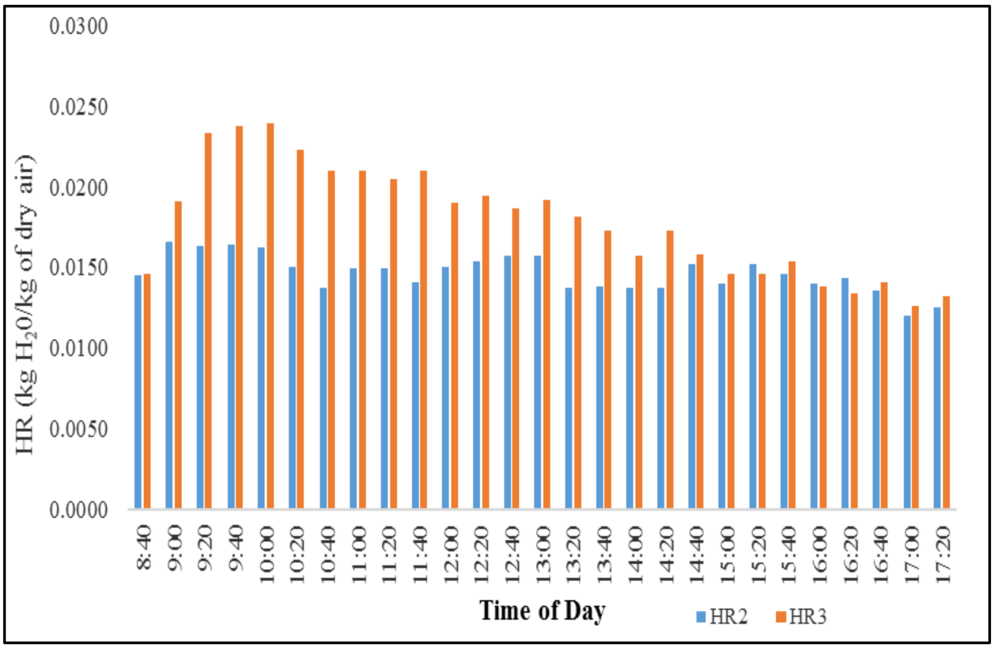


Figure 14. A graph of Humidity Ratio(HR) against time of drying

Table 1. Summary of calculated values.

Item No.	Description	Results	Eqn. No.
1	Area of collector (m^2)	0.56265m^2	
2	Collector inlet area (m^2)	0.00925m^2	
3	Average Irradiance(W/m^2)	525.29 W/m^2	
4	Evaporated moisture in kilograms of water	0.63551 kg	
5	Initial Moisture content of apples	86%	
6	Drying time	8hour 40 minutes	
	Time in seconds	31200 seconds	
7	Latent heat of vaporization (h_{fg}) kJ/kg at T_P=45 degrees)	2393.555 k J/kg	3
8	Quantity of heat required to evaporate the removed moisture (k J)	1521.125 KiloJoules	2
9	Total Collected Solar Energy (k J)	9226.61	10
10	Total Irradiance incident on absorber surface (watts)	260.1watts	5
11	Reflected Energy from Absorber(watts)	20.8 watts	6
12	Overall efficiency of solar dryer	16.49%	11
13	Energy falling on collector to units of energy(kWh)	2.56kWh	12
14	Average drying rate(g/s)	0.02037g/s	7
15	Percentage Moisture Removed from the product (%)	82.22%	8
16	Percentage final moisture content (%)	13.74%	9

The average irradiance was 525.29 W/m^2. The graph of irradiance against time was plotted as in Figure 12.

The results for temperature (in degrees Celsius), relative humidity (%) against time of the day was plotted as in Figure 13.

For this study, T1, T2, T3 are temperatures at collector inlet, drying chamber inlet and drying chamber outlet respectively, H1, H2 and H3 are relative humidity at collector inlet, drying chamber inlet and drying chamber outlet respectively. The results of other useful values for performance analysis are summarized as shown on Table 1.

The humidity ratios at drying chamber inlet (HR2) and drying chamber outlet (HR3) were also obtained. Graph of humidity ratio against time obtained from the results is as shown in Figure 14.

The dried product in the chamber was as shown in Appendix B.

5. Discussion and Conclusion

Airflow velocity distribution in the drying chamber was captured by Particle Image Velocimetry as shown in Figure 4. The distribution flow is fairly good with a high correlation coefficient as shown in Figure 7 and Figure 8. The correlation coefficient can be estimated to an average of 0.9, this implies a fair flow distribution. Imagery results for Turbulent Kinetic Energy indicates an average of 4.0 x 10-5 m^2/s^2 which implies fairly smooth airflow a characteristic of natural convection flow solar dryer.

To capture the temperature distribution, portable thermal imaging camera was used during actual drying time, the results shown in Figure 11 indicate a variation of 1.4°C in average temperatures between four sections categorized from the bottom of the drying chamber as Line1, Line 2, Line 3 and Line 4.

In order to test the solar dryer performance and relate the airflow study results to actual experiment data, fresh apples were dried and the results obtained during drying process are as shown in Figure 12 to Figure 14. Figure 12 shows the irradiance obtained at intervals of 20 minutes during drying period, the average irradiance was 525.29 W/m^2. Figure 13. shows a graph of temperatures and relative humidity at the collector inlet, drying chamber inlet and drying chamber outlet. From this graph, of great significance is the falling rate of relative humidity at the drying chamber outlet as the drying proceeds, this may be occasioned by the high relative humidity in the morning as well as high moisture extraction from the product during the initial stage of drying. Humidity ratios for the air at the drying chamber inlet and outlet were obtained by use of psychrometric chart and graph plotted as shown in Figure 14. The dropping humidity ratio of the air from the drying chamber can be related to the reducing rate of the moisture removal from the product as the % moisture content falls.

A summary of drying performance analysis results was tabulated as shown in Table 1. The prototype solar dryer had an overall useful efficiency of 16.47% after drying apples from moisture content of 86% (wet basis) to 13.74% (wet basis).

The objective of the study was achieved with a natural convection solar dryer suitable for mid-latitude application having been designed, fabricated and its performance evaluation studied. PIV technique was successfully applied for the airflow distribution and flow visualization. Thermal imaging was found useful in providing an idea on temperature distribution within the drying chamber. There was fairly uniform distribution of air across the trays from PIV study and that conformed to the results from experiments indicating uniform drying of the product across the trays.

The design for mid-latitude applications can easily be replicated elsewhere in the world at low cost, products can be dried in one day and the dryer has capability to dry products at commercial scale.

Acknowledgements

We acknowledge the support given by the management team of Ashikaga Institute of Technology more so the technical assistant and moral support from the teaching staff and post graduate students in Renewable Energy and Environmental Engineering Division.

References

[1] Ahmed Abed Gatea (2010). Design, construction and performance evaluation of solar maize dryer. *Journal of Agricultural Biotechnology and Sustainable Development*, Vol. 2(3), pp 039-046.

[2] A. A. El-sebaii, S.M Shalaby (2012). Solar drying of agricultural products: A review, pp 37-43. *Renewable and Sustainable Energy Reviews*, ELSEVIER.

[3] S. Misha et al (2013). Review on the Application of a Tray Dryer System for Agricultural Products. *world applied sciences*, Vol 22(3), pp 424-433.

[4] Suhaimi Misha et al (2013). The prediction of Drying Uniformity in Tray Dryer System using CFD Simulation. *International journal of Machine Learning and Computing*, Vol 3, No.5.

[5] Abdul Jabbar N. Khalifa et al (2012). An Experimental Study of Vegetable Solar Drying System with and without Auxiliary Heat, *ISRN Renewable Energy*, Hindawi Publishing Corporation.

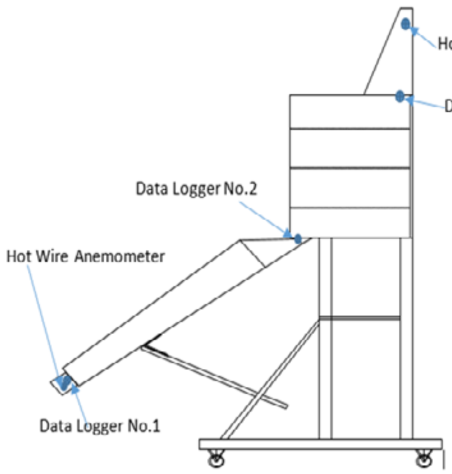
[6] Sandeep Panchal et al (2013). Design, construction and Testing of Solar Dryer with Roughened Surface Solar Air Heater, *International Journal of innovative Research in Engineering and Science*, Issue 2, Vol 7.

[7] Lyes Bennamoun (2012). An overview on application of Exergy and Energy for Determination of Solar Drying Efficiency, *International Journal of Energy Engineering*. 2(5), pp 184-194.

[8] A.O Adelaja and B.I Babatope (2013). Analysis and Testing of a Natural Convection Solar Dryer from Tropics, *Journal of Energy*, Hindawi Publishing Corporation.

Appendices

Appendix A: Solar Dryer set-up showing data logger (relative humidity and temperature) positions



Appendix B: Dried apples in drying chamber.

Dried apples in the drying chamber (before dryer modification)

Appendix C: Material used to fabricate the dryer.

Summary of Materials used for Construction of the solar dryer

Item No.	Material	Description
1	Plywood (Thermal conductivity 0.13W/m.K,)	Construction of the collector body, drying chamber, Chimney and supporting structures.
2	1 mm thick iron-sheet painted Matt- Black on one side.	Collector Absorber surface
3	Clear polycarbonate sheet (Transmissivity 0.88, thermal conductivity 0.19 W/m.K), thickness 0.15cm.	Cover sheet for collector.
4	Thick transparent polythene paper	Chimney cover, flexible termination of collector sheet to the drying chamber
	Silicon-Caulk	Sealant for intersections
6	Caster Wheels	Dryer foot for mobility
7	Nails and Screws	Joinery work and mounting
8	Matte-Black grade paint	Painting absorber surfaces
9	Door Hinges	Angular deflection point connection for collector to drying chamber, door hinges
10	Perpendicular angle brackets	Reinforcement of stands
11	Stainless steel Wire Mesh	Construction of product holding trays

NB. The 1mm thick iron-sheet has thermal conductivity 16.2W/m.K , Specific heat Capacity 500J/kg.K , Thermal diffusivity $4.2*10^6$m/s, absorptivity 0.92, Emissivity 0.95.