DESIGN, DEVELOPMENT AND TESTING OF A LIQUEFIED PETROLEUM GAS POWERED TOMATO DRYER WITH WATER ENERGY STOTAGE

By

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university or any other award.

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Date 25/5/2015

We confirm that the work reported in this thesis was carried out by the candidate under our supervision.

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DEDICATION

To my dear family

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ABSTRACT

Despite high levels of good quality tomato production in Kenya, about 40% of the produce goes to waste. This loss is attributed to glut during the harvesting season, poor feeder roads which lead to inaccessibility to the market centres as well as bruise damage during transport. This translates to a huge financial loss to tomato farmers. Preservation through drying technology can help in reducing this loss. Therefore, this study was initiated to investigate the performance of an experimental Liquefied Petroleum Gas (LPG) dryer with energy storage for tomato drying in rural and urban markets. LPG was chosen for the study because it can easily be substituted with biogas produced from biodegradable market wastes in order to operate under all weather conditions and hopefully reduce operational costs. The dryer was designed, developed, constructed and installed at the Appropriate Technology workshop, Kenyatta University, Nairobi, Kenya. The main components of the dryer were the thermal storage tank/boiler, heat exchanger, drying chamber and two 12V DC fans powered by two 50-Watts photovoltaic/200 Amp-hours battery electrical system. The thermal storage system was constructed from a 225-litre water heater tank (diameter 63.5 cm and height 109.2 cm) whose centre contains a cylindrical tube fitted with an LPG burner. The wall of the tank/boiler was made from 14gauge (2mm) galvanized iron sheet capable of withstanding 4 bar pressure. The boiler was well insulated with a composite wall comprising of a 2.5cm layer of vermiculite thickness, followed by 5cm layer of woollen blanket materials and finally covered with 2.5cm of plaster of Paris. A shell and tube single pass cross flow heat exchanger rated at 8.21KW comprising of five radiator panels each consisting of two 0.038m internal diameter sub-headers and fourteen 0.025m internal diameter finned risers all made from galvanized iron pipes was constructed and fitted onto the entrance of a rectangular drying cabinet fitted with wire mesh trays. Sliced fresh tomatoes were loaded onto the trays. The LPG gas was lit and then ambient air was forced into the heat exchanger and heat energy was recovered using 12VDC pusher and puller fans powered by two-50W PV panel and 200Ah battery and passed through the drying trays. Several runs were conducted with and without load and repeated six times. The results demonstrate that unloaded dryer with ambient air entering at an average of 25^{o}C and boiler maintained at 92^{o}C and low, medium and high air flows of 0.19, 0.23 and 0.28m^3/s respectively generated corresponding drying temperatures of 57.1, 54.4 and 52.5^{o}C respectively. It was also observed that at an air velocity 0.28m^3/s and drying air temperature of 52.5^{o}C, the dryer showed potential to dry 9kg tomatoes from 93.7% to 13% (wb) moisture content within 10.3 hours and consuming 10 kg of liquid propane gas. With a maximum air velocity of 0.43m^3/s and drying temperature of 43.3^{o}C, tomatoes were dried to moisture content of 8% but at a longer duration of 11.5 hours consuming 6kg liquid petroleum gas.

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LIST OF SYMBOLS AND ABBERVIATIONS

Symbols	Description	Units
A	Surface area of the heat exchanger	[M^2]
C_{pw}	Specific heat capacity of water	[kJ/kg/k]
C_{pa}	Specific heat capacity of ambient air	[kJ/kg/k]
C_t	Specific heat capacity of tomatoes	[kJ/kg/k]
Brix	Solid content in the pulp as measured by refractometer	
ΔT_c	Temperature change for tomatoes during drying	[^oC]
ΔT_w	Temperature change for water in the heat exchanger	[^oC]
F_{ex}	Correction factor of a heat exchanger	[Dimensionless]
M_a	Mass flow of air	[kg/s]
M_w	Mass flow of water	[kg/s]
Mc	Weight of fresh tomatoes	[kg]
M_s	Thermal storage mass requirement for water	[kg]
M_{Wt}	Mass of water removed from tomatoes	[kg]
M_{Wi}	Initial weight of tomato sample	[g]
W_t	Weight of tomato sample at time "$_t$"	[g]
P	Atmospheric pressure	[101.3 kPa]
W_1	Initial moisture content (wb) of tomatoes	[%]

W_F	Final moisture content (wb) dry tomatoes	[%]
$\frac{dm}{dt}$	Drying rate	[g water/g solid.hr]
M_t	Moisture content (db) at weighing interval	[%]
M_{t-1}	Moisture content (db) at previous weighing interval	[%]
t	Weighing time interval	[hr]
P_{ex}	Effectiveness of a heat exchanger	[Dimensionless]
R_{ex}	Capacity ratio of a heat exchanger	[Dimensionless]
R	The specific gas constant	[0.287 kPa m^3/kgk]
T	Absolute temperature	[K]
$T_{w, in}$	Temperature of water entering the heat exchanger	[^oC]
$T_{w, out}$	Temperature of cooled water exiting the heat exchanger	[^oC]
$T_{a, in}$	Temperature of air ambient entering the heat exchanger	[^oC]
$T_{a, out}$	Temperature of heated air exiting the heat exchanger	[^oC]
T_1	Inlet (high) air temperature into the dryer	[^oC]
T_2	Outlet air temperature from the dryer	[^oC]
ΔT_{lm}	Log-mean temperature difference	[^oC]
q	Rate of heat transfer	[kJ/s]
Q	Energy requirement of the heat exchanger	[kW]
V_a	Volume of air	[m^3]
V_{et}	Necessary expansion tank volume	[Litre]
V_w	Water volume in the system	[Litre]

η	Efficiency	[%]
v_0	Specific volume of water at initial (cold) temperature	[m^3/kg]
v_1	Specific volume of water at operating (hot) temperature	[m^3/kg]
U	Overall heat transfer coefficient	[W/m^2K]

Abbreviations	**Description**
ACRE	Australian Cooperative Research Centre for Renewable Energy
CFM	Cubic feet per minute
HCDA	Horticultural Crops Development Authority
ICAR	Indian Council of Agriculture and Research
ITDG	Intermediate Technology Development Group
LPG	Liquefied Petroleum Gas
UNEPE	United Nations Commission for Europe

CHAPTER ONE: INTRODUCTION

1.1 Background

Worldwide post-harvest fruit and vegetables losses are as high as 30% to 40% (Burden, 1989; Herregods, 1998; Hewett, 2003). The Kenya government has placed agriculture and rural development at the top of the list for national priorities for action (Republic of Kenya, 2001). Although improved agricultural productivity can simultaneously improve the welfare of the agriculturalist as well as the urban poor (Haggblade, 2004), it cannot alone ensure a country's food security; a key rural economic indicator (Government of Kenya, 2006) without preventing losses from harvesting to consumption. Out of the total national horticultural production of about 3.2 million tonnes in year 2002 about 121,000 tonnes constituting only 4% was exported, 4,000 tonnes were supplied to the agro-processing industries, and the balance was consumed in the fresh local market (Songa and Gikonyo, 2005). Tables A-1 and A-2 in Appendix A shows the growth in exports and export product values respectively from 1992 to 2003.

Poor road network in the rural areas coupled with increasing competition from Common Market for Eastern and Southern Africa (COMESA) imports into the local market has led to high post-harvest losses as only a limited harvest access the local market and is actually consumed (Songa and Gikonyo, 2005). Part of the produce that accesses the local market suffers from mechanical injury during transport (Figure 1.1) making them unfit for sale (Figure 1.2) while the healthy

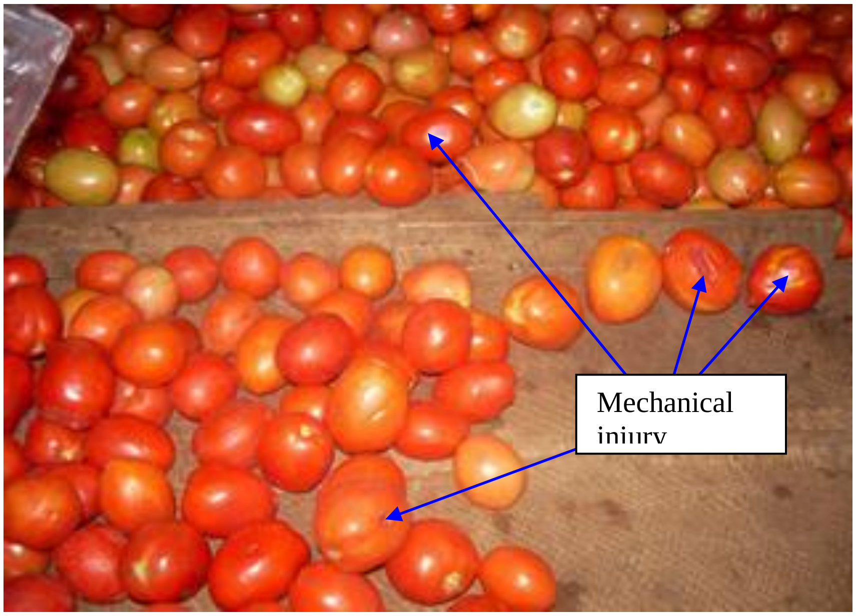


Figure 1.1 Tomatoes on sale at Githurai open air market, 25km East of Nairobi, Kenya

Figure 1.2 Mechanically injured tomatoes become unsaleable

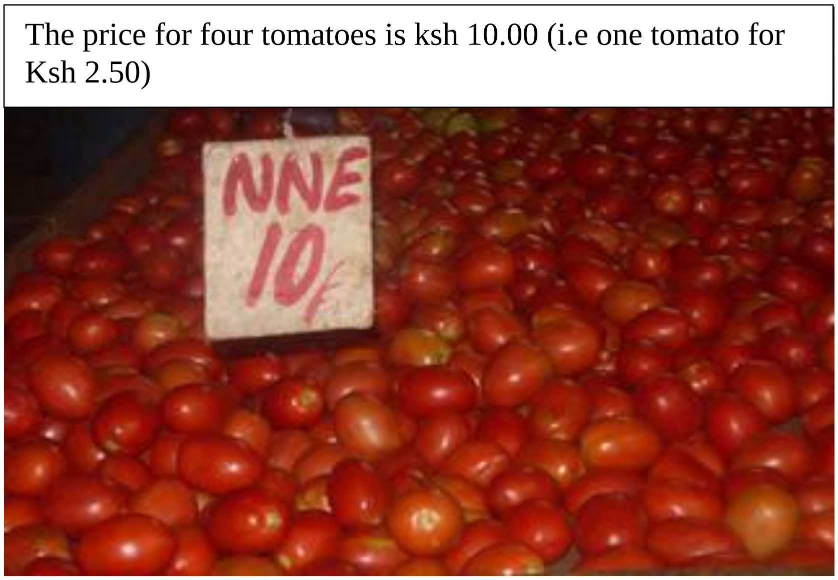
ones also loose their freshness very quickly due to their short storage life. There is a need to dry both fruits and vegetables not only for preservation but also to diversify and add value in order to make them competitive in the market and fetch better prices.

1.1.1 Storage of fresh tomatoes

The tomato consignments that reach the market consist of a mixture of green, pink and red tomatoes as shown in Figure 1.3. It is in this form when their price is highest. The storage life of tomatoes is greatly influenced by respiration and water loss both of which lead to weight loss and thus a direct marketing loss (Thanh, 2006). Respiration may be aerobic or anaerobic and is measured by the amount of oxygen consumed or the amount carbon dioxide produced over a given time respectively. During respiration tomatoes lose 10-20 mg CO_2/kg-h. This leads to loss of dry matter and hence weight loss. In dry air, they may loose 5–10% of weight as water. This makes them wilt or shrivel and they lose the appearance of being “fresh”. The price then drops progressively to about 70% as they loose there freshness as shown in Figures 1.3, 1.4, 1.5 and 1.6. Table A-3 shows the maximum percentage water loss at which commodities become unsuitable for sale. The recommended storage temperature varies with the maturity of the fruit (for mature green, 15.5^{o}C; for pink, 10^{o}C). The maximum storage life is 2-4 days for red, 7-14 days for pink and 21-28 days for mature green tomatoes (Boyette *et al*., 2004). Refrigeration is not recommended as it may cause flavour loss.

The price for three tomatoes is ksh 10.00 (i.e one tomato for Ksh 3.33)

Figure 1.3 A mixture of green, pink and red fresh tomatoes soon after arrival at Githurai open air market



The price for four tomatoes is ksh 10.00 (i.e one tomato for Ksh 2.50)

Figure 1.4 Ripe tomatoes on sale at Githurai open air market

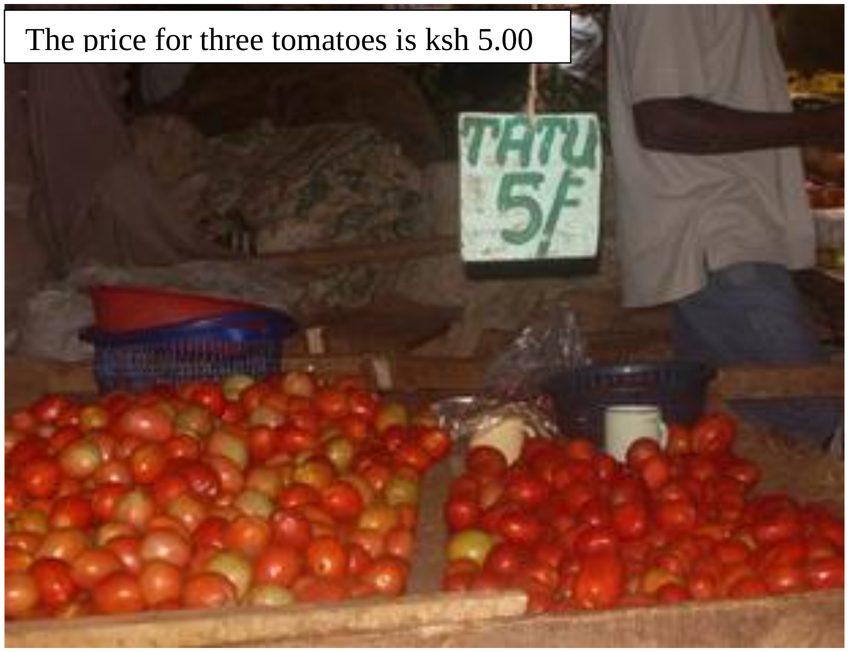

The price for three tomatoes is ksh 5.00

Figure 1.5 A new consignment (shown on the left) while the old consignment (on the right) continues to lose value


The price for one

Figure 1.6 Rotting tomatoes

1.1.2 Nutritional and medicinal value of tomatoes

Tomatoes contain nutrients such as beta-carotene, vitamins C and E, and lycopene which is an antioxidant (Agarwal *et al*., 2001). Consumption of processed tomato products has been credited with reduction of prostate cancer (Gaster, 1997; Turner, 2002), decreased ozone and cigarette smoke induced DNA damage to the lungs (Kim *et al*., 2000) and retardation of development of blood clots (Dutta-Roy, 2000).

1.1.3 Preservation of tomatoes

1.1.3.1 Preservation by processing

Tomatoes can be processed into tomato based products such as paste, puree, jam, chutney, ketchup and soup. These products differ on the final solid content in the tomato juice and also on the type of ingredients added to the pulp as shown on Table A-4 in Appendix A. The products are preserved by hot water pasteurizing in sealed bottles at 90-100^{o}C for at least 10 minutes followed by cooling at room temperature (ITDG, 2006).

1.1.3.2 Preservation by drying

The optimum drying temperatures of tomatoes range between 50-60^{o}C (Zanoni *et al*., 1998; Shi *et al*., 1999; Parnell *et al*., 2004). When dried at too low temperatures (less than 32^{o}C) the product dries too slowly with growth of mould or bacteria. At temperatures of 77^{o}C and above, tomatoes harden on the outside while the inside remains moist allowing spoilage (Parnell *et al.*, 2004). The common drying method is open-air (Kitina, 1992). Domestic electric ovens and dehydrators are sometimes used for drying. Cooled dried tomatoes should be packed in air tight bags and stored in a cool (15.5-21^{o}C), dark place for up six to eight months or frozen for up to one/one and a half year/s. Classification of dried tomatoes by United Nations Commission for Europe (UNEPE) is as shown on Table A-5.

1.2 Problem statement

Despite high levels of tomato production in Kenya about 40% of the produce goes to waste. This loss is due to market glut, poor feeder roads which lead to inaccessibility to the market centres as well as bruise damage during transport. This translates to a huge financial loss to the farmer. There is a need to preserve the product for cooking out of season and/or to add value for export (ITDG, 2006). Preservation by drying can help in reducing the loss and therefore, a low cost LPG dryer was proposed. LPG gas was chosen for the study since it can easily be substituted with biogas for large scale operations in order to lower operational costs especially in rural farmlands.

1.3 Justification

A successful outcome of the study will allow farmers to harvest their tomatoes with some flexibility; more independently of the prevailing prices in the market since dried products can be stored for longer time periods, making them a regular source of income. It will also lead to the extension of the dryer unit as it regard to its capacity and in drying other horticultural products. Farmers will be encouraged to set up biogas systems and use animal dung and crop waste to generate biogas to power the dryer. In the urban markets, biodegradable wastes collected from the markets may be used as a feedstock for biogas systems to generate biogas to power the dryer. This will offer a sustainable solid wastes management practice in the urban centers. Overall, the livelihoods of rural and urban poor will be improved through the development of tomato based post-harvest technology.

1.4 Objectives

1.4.1 General objective

The general objective is to develop a low cost LPG powered system with energy storage and PV-battery driven fans for tomato drying in rural areas and urban markets.

1.4.2 Specific objectives

Specific objectives of this project are to:

(i) Design an LPG gas powered dryer with energy storage for tomato drying to supplement solar drying.

(ii) Construct LPG powered dryer for tomato drying.

(iii) Test the LPG dryer for tomato drying.

(iv) Carry out economic analysis of the LPG dryer for tomato drying.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Drying is one of the oldest methods of preserving food. Today, drying of foods is still an important method of preservation. Dried foods can be stored for long periods without deterioration occurring. The principal reasons for this are that the microorganisms (bacteria, yeast and mold) which cause food spoilage and decay cannot to grow and multiply in the absence of sufficient water and many of the enzymes (naturally occurring substances which cause foods to ripen) which promote undesired changes in the chemical composition of the food cannot function without water. Drying of foods implies the removal of water from the foodstuff and as a result the food becomes smaller and lighter in weight. In most cases, drying is accomplished by vaporizing the water that is contained in the food, and to do this the latent heat of vaporization must be supplied. Earle (1983) singled out the two important process-controlling factors that enter into the unit operation of drying as;

(a) Transfer of heat to provide the necessary latent heat of vaporization,

(b) Movement of water or water vapour through the food material and then away from it to effect separation of water from foodstuff.

The energy, which must be supplied to vaporize the water at any temperature, depends upon this temperature. The quantity of energy required per kilogram of water is called the latent heat of vaporization, if it is from a liquid, or latent heat of sublimation if it is from a solid. The heat energy required to vaporize water under any given set of conditions can be calculated from the latent heats given in the steam table shown on Table A-6 since water vapour and steam are the same thing (Earle, 1983).

2.2 Crop drying principles

2.2.1 Electric powered driers

In these types of dryers, ambient air is electrically heated up to the target drying temperature before being forced into the drying chamber by electrical powered fans. The electrical heating element is wired to a thermostat (placed in the drying chamber) which controls the switching ON and OFF of power supply to the heater so as to main the target temperature. The fans ran throughout the drying period. Electrical drying is an energy intensive method (Thompson *et al*., 1978). Provided sufficient value is added by drying to cover electricity costs, such dryers offer distinct advantages over solar dryers which include; greater daily output, higher drying temperatures and thus considerably more rapid drying, faster drying due to the forced air flow, total independence from weather conditions and good control of the drying process (ITDG). However, the national access to electricity in Kenya is slightly above 15% covering mostly the urban centres clients. This renders electrical driers unsuitable in the rural areas where farming is practiced. Even in the areas connected to the power grid, power supply is irregular due power rationing usually occasioned by power equipment outages as well poor hydrology.

2.2.2 Fossil fuel powered dryers

The dryers consist of a cabinet containing trays which is connected to a source of air heated by either natural gas, liquid petroleum gas (LPG), kerosene, diesel or oil. Diesel powered driers are inefficient and may pollute the product with diesel fumes and sulfur. Propane which is a type of LPG gas is an excellent choice for fueling the burners of fruit dehydrators because it is nontoxic and safe around food materials. Emissions from propane burners are significantly lower than those from oil-fueled burners. While propane can be stored for extended periods of time, gasoline and diesel fuel tends to turn rancid. Furthermore, gasoline and diesel fuel spills can contaminate water, land, and crops while any LPG leak vaporizes instantly (Illinois Propane Gas Association, 2009). In general, the use fossil fuels as a primary source of energy for drying is hampered by the instability of the crude oil prices which can result into high drying costs (Farm press, American agriculturalist, 2005). Fossil fuels are also finite energy resources.

2.2.3 Ambient air drying

Ambient drying refers to drying with unheated air. Due to increasing energy costs and scarcity of fuel supplies, research into natural air drying of walnuts was started at the Agricultural Engineering Department at the University of California in 1977 (Thompson *et al*., 1978). The use of unheated ambient air replaced the energy intensive method where ambient air was electrically heated up to 43^{o}C before being forced through a fixed bed dryer by electrical powered fans.

However, electrical powered fans were retained to force the ambient air into the fixed bed dryer. Initial field trials showed the feasibility of drying walnuts with ambient air. Average fan energy requirements ranged from 9.32-22.7 kWh/t. At US 5 cents per kWh, the corresponding electrical energy costs ranged from US 47 cents to $1.14/t (metric ton). This represented savings of over $12/t over the average 1981 costs of $13.75/t for walnuts dried with heated air (Thompson, 1981). They also demonstrated that with similar air velocity in each system the ambient drying required three times more fan operational time but the whole process was more economical in the long run. Ambient air drying showed the potential of reducing the total energy costs (gas and electricity) by 90% over the convectional heated air without reducing quality (colour, mould, insects' damage).

2.2.4 Open air drying

Most crops produced in the remote areas of developing countries are dried using the open-air sun drying method. Sun drying is the cheapest method in terms of construction (Figure 2.1), however large scale sun drying requires an extensive drying ground (Figure 2.2). The quality of the dried products is poor due to contamination of the product by insects, dirt, rain and discolouration due to ultra-violet radiation (Esper and Muhlbauer, 1996). The drying rate depends on the temperature and humidity of the ambient air (Kitina, 1992). A minimum temperature of 30°C and a relative humidity of below 60% are recommended for fruits and vegetables. An improvement of product quality and reduction of losses can only be achieved by the introduction of suitable drying technologies.

Figure 2.1 Open sun drying structure Tembo *et al*. (2008)

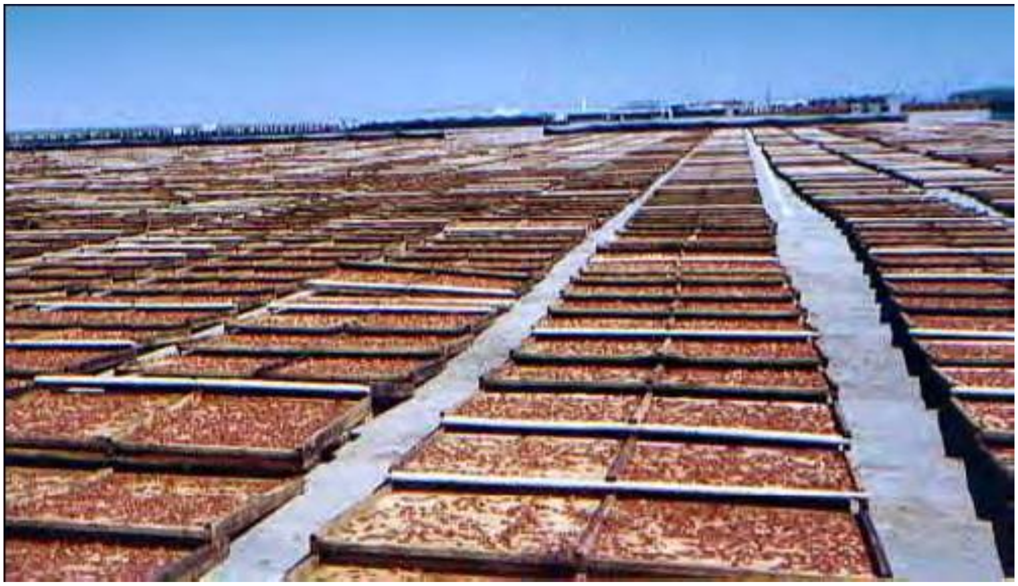


Figure 2.2 Large scale open sun drying

2.2.5 Solar drying

Solar drying is an elaboration of sun drying and is an efficient system of utilizing solar energy (Bala, 1997a & 1998, Zaman and Bala, 1989). They have been developed with an objective of increasing the drying rate and improving quality of the produce. Studies have shown that solar dryers are economically viable (Eckert, 1998; Green and Schwarz, 2001) and that the use solar dryer leads to a shorter drying time and high quality products compared to open air sun drying (Sharma *et al*., 1994; Villaruel, 1996; Worner, 1997).

A solar coconut dryer built in Philippines and tested between 1994/1995 had a drying time of 4-5 days with 50% of the coconuts maintaining their white colour against 5-7 days with less than 20% of the end product maintaining their white colour for open air sun drying (Green and Schwarz, 2001). However, it is difficult to control drying temperature and the drying rate may be limited (Bala and Janjai, 2009). Oosthuizen (1995) identified part of this failure due to the fact that the dryers have usually not really been matched to the design requirements.

2.3 Classification of solar dyers

Solar driers may be classified according to the mode of airflow (convection or forced convection solar dryers) or according to how solar energy reaches the product in the dryer (direct, indirect or mixed mode solar dryers).

2.3.1 Natural convection solar driers

In the natural convection solar dryers the airflow is established by buoyancy induced airflow. These types of driers have advantages over forced convection solar drying due to lower investment, operation and maintenance costs. The use of natural convection solar dryers is however limited by their small holding capacity and inadequate rate of moisture removal (Gnanaranjan, 1997). This makes them not suitable for small scale industrial production of fruits, vegetables, spices, fish and medicinal and herbal plants.

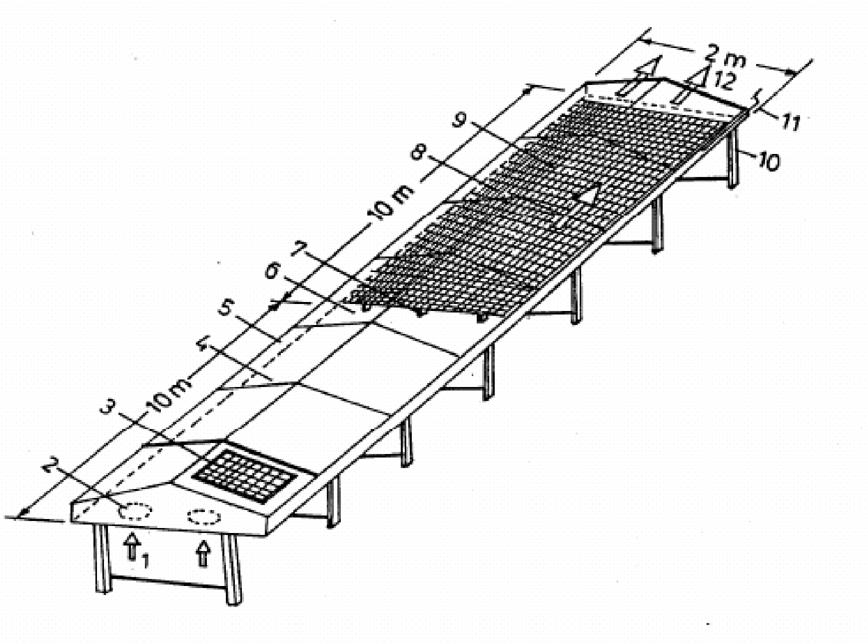
2.3.2 Forced convection solar dryers

The limitations of natural convection dryers prompted researchers to develop forced convection solar dryers. The airflow is provided by using fan operated either by grid connected electricity or solar module. Examples of these dryers are (i) solar tunnel drier (Esper and Mühlbauer, 1993), (ii) Indirect forced convection solar drier (Oosthuizen, 1996), (iii) Greenhouse type solar drier (Janjai, 2004), (iv) Roof integrated solar drier (Janjai, 2004) and (v) Solar assisted dryer (Smitabhindu, 2004). Numerous tests in the different regions of the tropics and subtropics have shown that fruits, vegetables, cereals, grain, legumes, oil seeds, spices, fish and even meat can be dried properly in the solar tunnel dryer (Muhlbauer *et al*., 1993; El-shiatry *et al*., 1991; Esper and Muhlbauer, 1993, 1994 & 1996; Bala, 1997b, 1999a&b, 2000 and 2004; Bala *et al*., 1997, 1999, 2002 and 2003 and Bala and Mondol 2001).

2.3.3 Solar tunnel dryer

The University of Hoheinheim, Germany introduced a forced convection solar tunnel dryer that incorporated PV powered fans. The width of the solar collector and the tunnel drying unit dryer were 2m wide, while their lengths were 8m and 4.3m, respectively (Esper *et al*., 1994; University of Hoheinheim, 1996). Both of the collector and tunnel drying unit were covered with ultra violet stabilized plastic sheet and connected in series. To prevent the entry of water inside the drier unit during rain, the cover was fixed like a sloping roof. The products to be dried were placed in a thin layer in the tunnel drier. The whole system was placed horizontally on a raised a platform. The airflow was provided by two DC fans operated by a photovoltaic module. Since the air is passed over the product rather than through the product in the drier, the power requirement to drive a fan is low. The dryer had a capacity of 1.5kg/m^2 for medicinal plants and 25kg/m^2 for grapes. A variety of agricultural products were economically dried.

A small size solar tunnel dryer tailored for small-scale farmers with a dryer and collector width of 1.8m and length of 4m and 4.3m respectively was fabricated (Mastekbayeva *et al.*, 1998). Its full load capacity was 85kg of fresh chilli per batch. The drying time for 19.5kg of fresh chilli with PV powered fans was reported to be one third that of natural convectional solar dryer. They associated the better performance of PV operation with the passive control of airflow by the solar radiation. A typical arrangement of a solar tunnel dryer is shown in Figure 2.3.



Legend

1. Air inlet
2. Fan
3. Solar module
4. Solar collector
5. Side metal flame
6. Outlet of the collector
7. Wooden structure
8. Plastic net
9. Roof structure for supporting the plastic cover
10. Base structure for supporting the tunnel dryer
11. Rolling bar
12. Outlet of the drying tunnel

Figure 2.3 A typical arrangement of a solar tunnel drier, Bala and Janjai (2009)

2.3.4 Direct solar dryers

In direct solar dryers, the collector and drying chamber are in the same transparent enclosure and the food is exposed to the sun rays as shown in Figure 2.4. To further enhance the efficiency, the internal surfaces of the enclosure are painted black. The heat generated from the absorption of the solar radiation within the

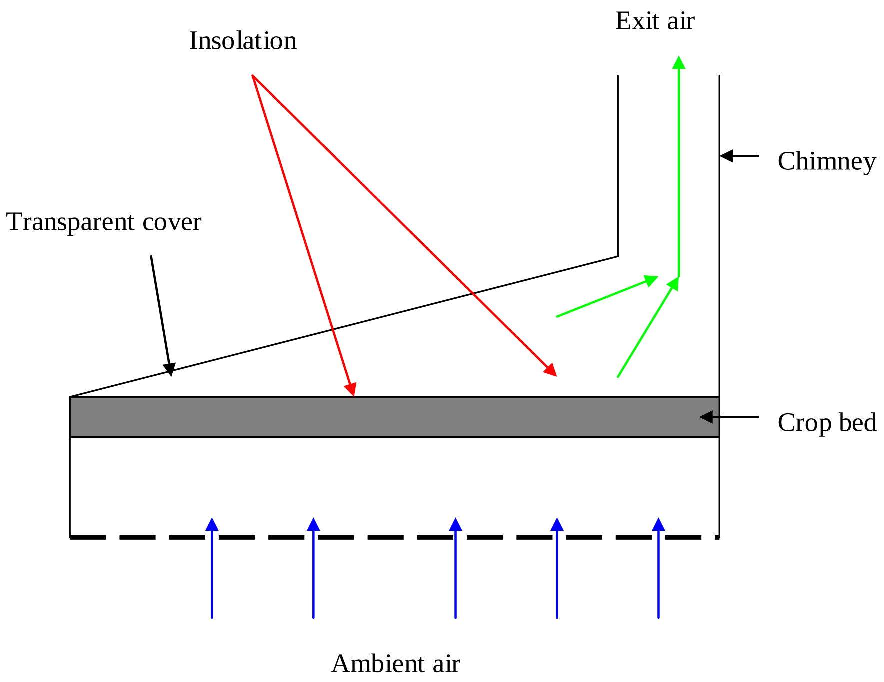


Figure 2.4 Typical arrangement of a direct dryer

crops as well as the surfaces of the enclosure causes the removal of moisture. They are simple to construct, and more hygienic than open-air sun drying. They can heat the crops to temperatures higher than those achieved by sun drying. However, they are known to suffer from many problems such as overheating, and changes in crop color and flavor due to the direct exposure to sun.

Unless they are built in large sizes, direct dryers can only dry small quantities of crops, because they use the same ground area as that which the traditional sun drying requires. Another major disadvantage of direct dryers is the difficulty in controlling the rate of moisture removal. At the start of the drying process, it is often necessary to close al1 the outlet air holes to allow the temperature of air in the dryer to rise. Water evaporates from the crop and condenses on the inside of the transparent cover and thus reducing the amount of solar radiation transmitted to the dryer interior. This condition is subsequently improved by opening the outlet vents, but in turn it causes temperature inside the dryer to fall. Direct systems are used for food such as raisins, grains and coffee where the colour change caused by the sun is acceptable, but most foods need indirect systems to protect the colours in the food. Figure 2.5 shows a simple direct dryer constructed from transparent polythene bag.

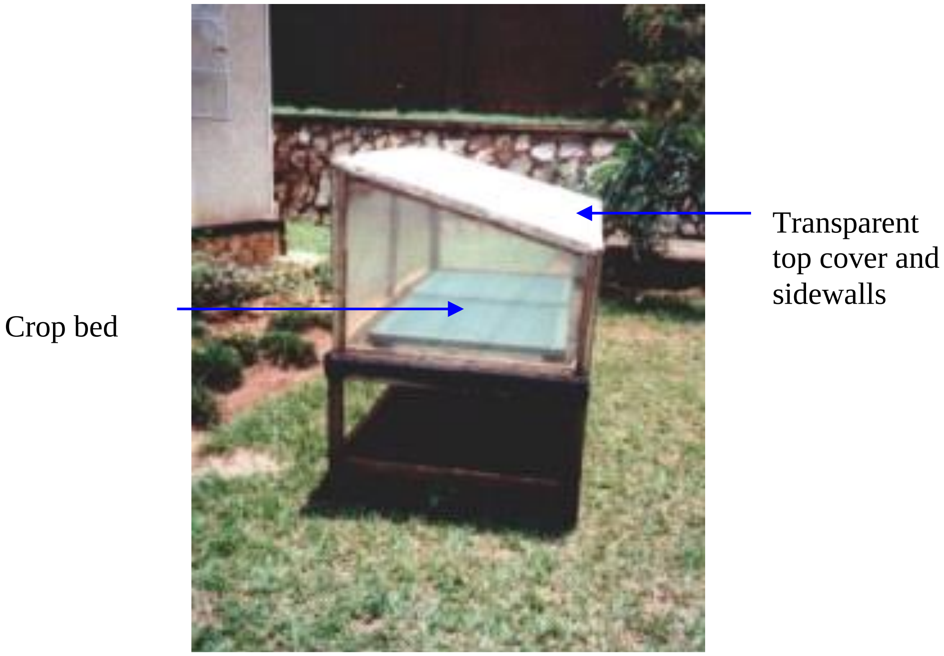
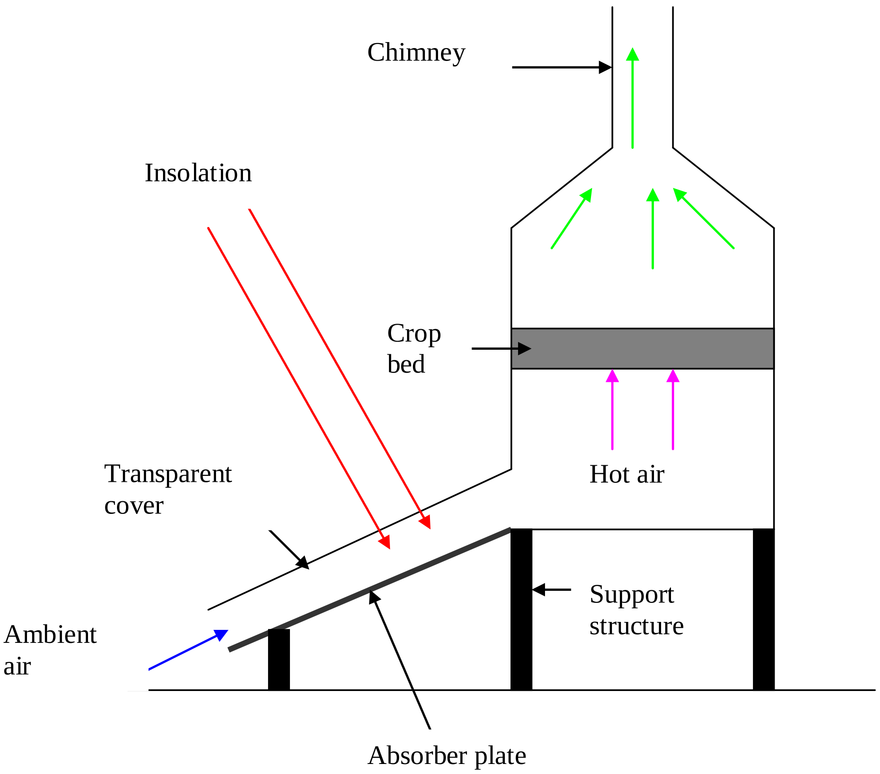


Figure 2.5 A direct dryer

2.3.5 Indirect solar dryers

In indirect solar dryers, the collector and drying chamber are separate. A chimney is usually incorporated in natural convection indirect dryers to increase the airflow through the crop bed (Figure 2.6). The collector heats up the air, which rises by convection forcing its way through the racks of drying produce in the drying chamber. The air passes through the wet crop bed and becomes nearly saturated, thus lowering its temperature to nearly that of the ambient air, before it exits via a chimney. This type of dryer is used when the crop being dried can be damaged if it is exposed to the direct rays of the sun. Crops can be dried in deeper layers, therefore saving ground space. However the drying rate is low due to poor airflow (Oosthuizen, 1996). The poor airflow rate is because the air above the crop bed is not substantially different in temperature from that of ambient air, hence the resulting buoyancy forces, which are proportional to the temperature difference, are very small, and in turn produce very low air-flow rates (El-lamushe, 1998).



2.5.5.5 Mixed mode solar dryers

Figure 2.6 Typical arrangement of an indirect natural convection dryer

2.3.6 Mixed mode solar dryers

These are a combination of direct and indirect solar dryers. They are normally indirect dryers with transparent drying chamber tops and/or sides. Mixed mode dryers are best suited to drying crops to which the exposure to sunlight is considered essential for the required color or flavor development in the dried produce.

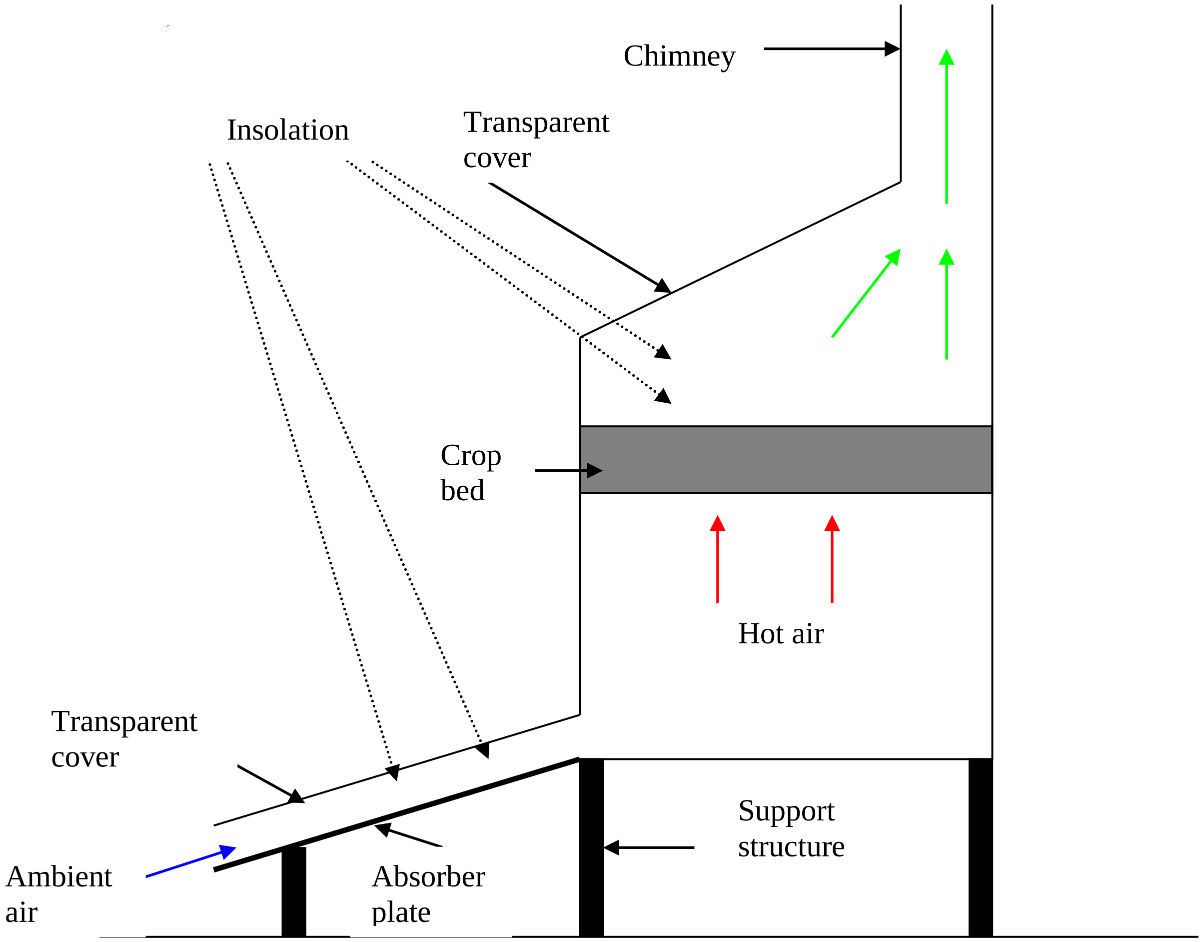


Figure 2.7 Typical arrangement of a mixed mode natural convection dryer

Examples of the dried produce include Arabic coffee, dates, and certain varieties of raisin grapes. A sketch of a mixed mode dryer is shown on Figure 2.7. The mixed mode dryer and AIT drier are improvement over the indirect natural convection solar dryer (Bala, 1998). Kenyan black box dryer which is a mixed mode solar dryer shown in Figure 2.8 is claimed to be appropriate for small scale drying (Eckert, 1998). However both open air and all types of solar dryers are limited to local weather conditions and day time hours.

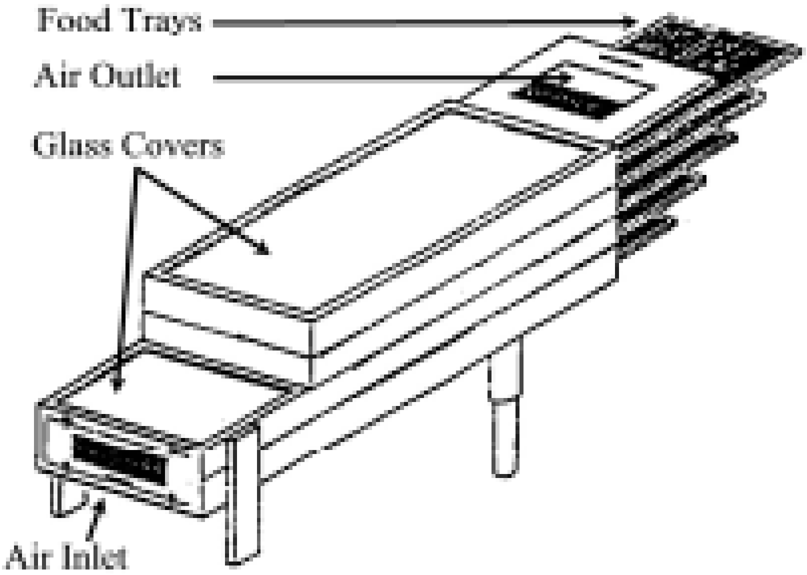


Figure 2.8: Kenya black box solar drier (Eckert, 1998)

2.4 Biomass energy resources for crop drying in Kenya

The agricultural activities generate a lot of biomass waste such as rice husks, coffee husks, maize straw, corncobs, sawdust, coffee stalks, tea stalks, coconut and macadamia nut shells**.** These residues are vastly under-utilised (ACRE, 1999). Tapping these residues could lead to economic growth, foreign currency saving, employment generation, and environmental management for the countries concerned. Until 1997, the Ahero and Mwea mills processed 80% of all Kenya's rice.

The annual throughput was 30,000 tonnes of paddy per annum, which generated 6,600 tonnes of husk. A further 1,650 tonnes were generated by dispersed rice growers in rainfed cropping areas, mostly in Coast Province. A dispute between the National Irrigation Board (NIB) and the farmers of 1997 led to the emergence of a large number of private and cooperative mills in these two localities which negatively affected generation of rice husks. Mwea alone has over 200 such mills the largest processing not more than 4 tonnes of paddy per day. Since then, farmers virtually stopped processing their rice at these (Mwea and Ahero) mills thereby reducing the combined annual paddy throughput for both Mwea and Ahero to below 900 tonnes. With 22% by mass of rice paddy being rice husks this translates to a drop in annual rice husk production from 7000 tonnes to less than 200 tonnes (C.S.T.S, 2004).

In addition to the low output the quality of rice husk currently produced is of poor quality and is dispersed over multiple sites and hence much harder to consolidate. The poor quality has been caused by the small-scale processors carrying out both milling and polishing of rice as a combined process. The by-product of the combined process is powdery bran rather than true rice husks produced by large millers. Powdery bran is much harder to handle than fibrous rice husks and would carbonise poorly. Rice husk is currently used as feed supplement for animals, horticultural mulch and in strengthening of burned bricks (C.S.T.S, 2004).

The use of rice husks as a fuel is further hindered by their costly conversion methods such as densification, briquetting and gasification. Their low energy content which is as a result of their high inert carbon content is a major hindrance to gasification process. Gasification of rice husks leads to the production of large quantities of ash due to large quantities of ungasified carbon. This ash requires constant removal thus slowing the process. Furthermore, the alkaline oxides of potassium and sodium present in the ash change from solid to liquid during pyrolysis of the husks present removal problems (Ong'or, 1996).

2.5 Liquefied petroleum gas as an alternative fuel in Kenya

Majority of the population rely on wood based biomass fuel for cooking and heating. To avert deforestation, the Government of Kenya offered fuel wood users LPG as an alternative fuel by introducing incentives such as removal of VAT in 2004 and Common External Tariff in 2005 (Mugambi, 2006). They further set 1st October, 2006 as the deadline for standardization of LPG regulators, a move that was aimed at bringing down the cost LPG appliances which was brought about by incompatibility of regulators between major dealers (Mugambi, 2006). There have been plans by Kenya Pipeline Company (KPC) to construct bulk LPG storage facilities in Mombasa and Athi River which is expected to further bring down the cost of LPG and maintain a constant supply (Mugambi, 2006; Gikunju, 2006). The Kenya Petroleum Refineries (KPR) is also undergoing modernisation to boost LPG gas production from the current 28,000 to 115,000 metric tonnes annually (Daily Nation Correspondent, 2006).

2.6 Hybrid dryers

2.6.1 Solar-biomass hybrid dryers

The drying process must continue uninterrupted until the final moisture content is obtained. This prevents moisture re-absorption and mould growth during overnight storage by the product from the surrounding air (Aboun-Enein *et al*., 2000). The seasonal variation in weather and the intermittent nature of solar energy often cause difficulties in sun and solar drying, due to high relative humidity and low solar radiation and thus the need to develop hybrid dryers. The use of solar dryers incorporating a biomass stove as a secondary source of heat will not only overcome the unreliability problem encountered by solar dryers but will limit the use of biomass as a primary source of energy. The biomass stove should only come into use during bad weather or at night.

2.6.2 Solar-sawdust hybrid dryer

Bassey (1985) reported a hybrid dryer that utilized direct solar energy and steam produced from a sawdust burner. They consisted of a sawdust burner and cabinet dryer fitted with three drying trays. The dryer cabinet had a 2m^2 glass cover and double walls separated by a 10 cm insulating layer of wood shavings. Several 2.5 cm diameter holes were perforated on the base and sides of the drying cabinet for inlet and outlet air respectively. The six pipes shown in the cabinet supplied heat to the three trays. Four galvanized iron evaporator pipes (110cm long, 1.27 cm diameter) connected to 6.5 cm diameter header pipes were mounted directly over the burner holes. Results of tests, for no load and using okra (Hibiscus esculentus L.), showed the dryer, operating at temperatures between 40 and 70°C, and could dry twice faster than the traditional open air method. The general features of the dryer are shown in Figure 2.9.

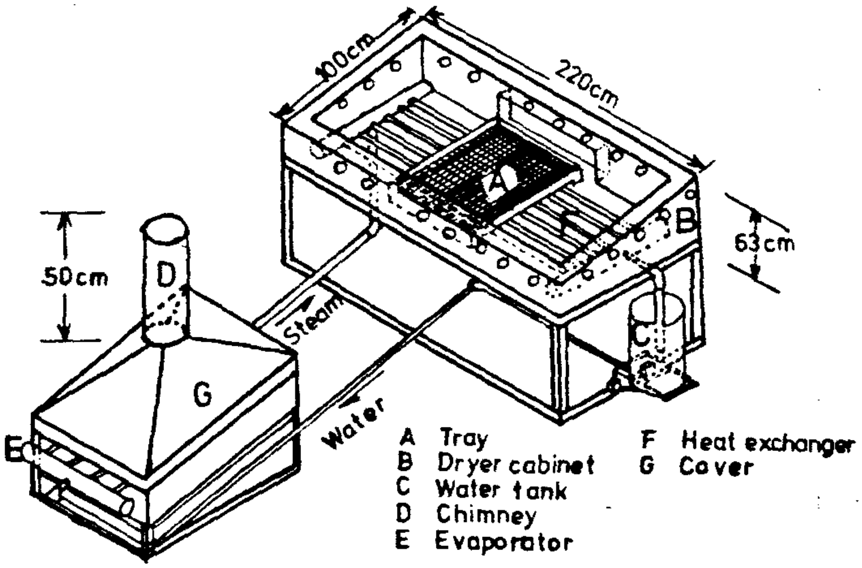


Figure 2.9: A solar- sawdust burner hybrid dryer (Bassey, 1985)

2.6.3 Solar-rice husk hybrid dryer

Mastekbayeva *et al*. (1998) reported a hybrid dryer consisting of solar tunnel dryer and rice husk briquettes fuelled stove to complement solar energy. Six fans each rated 14W with a total air handling capacity of 130m^3/hr were used to force air into the solar collector. The rate of fuel consumption was estimated to be 2.44kg/hr. A drying time of 12 hours for both chilli and ear lobe was reported against 2-5 days in ‘solar only operation’. The final dried product was of better quality compared to open sun and solar drying. The solar-biomass hybrid tunnel dryers seemed to offer an attractive and reliable drying method as they overcome the limitations of solar drying during cloudy days, and also enable drying during nighttime. The facilitating of continuous year-round operation of the dryer thus improves the financial viability of the dryer considerably. The pictorial of the dryer system is shown in Figure 2.10.

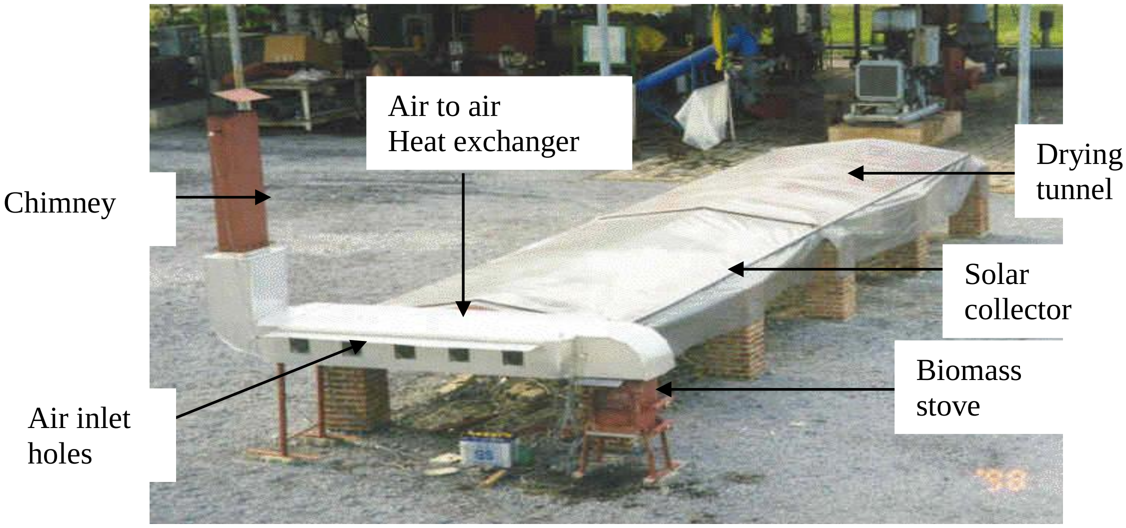


Figure 2.10: Solar-rice husk hybrid dryer (Mastekbayeva ***et al***., 1998)

2.6.4 Solar-producer gas hybrid dryer

Drying of chilli using producer gas from an Up Flow gasifier has been reported (Asasujarit *et al.*, 1996; Bhattacharya *et al.*, 2000). Pairintra *et al.* (1997) reportedly dried garlic using a solar-producer gas hybrid dryer. The drying time and average temperature were 14 hours and 55.6^{o}C with solar only against 15 hours and 45.4^{o}C with solar-producer hybrid system. In both cases the airflow rate was 0.17kg/s and initial and final moisture content of 67 % (wb) and 6% (wb) respectively.

2.6.5 Solar-LPG hybrid dryers

Although hybrid dryers that incorporate a secondary biomass heat source may solve the unreliability problem, excessive use of biomass may lead to loss of biodiversity. This has prompted researchers to develop solar-fossil fuel hybrid dryers. A forced convection solar-LPG hybrid dryer for tomatoes consisting of 60m^2 of packed-bed solar-air heater, tray-type dryer, 3kW capacity electric blower (air handling capacity 3000 m^3/hr) has been reported in India (ICAR, 2004). The drying time for one batch was 10 hours. The system worked with solar-air heater for 6-7 hours and 2-3 hours with LPG backup.

2.7 Geothermal energy

Several researchers have found low temperature geothermal energy a potential source of energy for heating drying air needed for dehydration (Thiebrat *et al*., 1997; Lienau, 1998; Lund, 2000). Andritsos *et al*. (2003) studied the use of geothermal energy in tomato drying. The drying chamber was a 14m long, 1m wide and 2m high rectangular made from polyurethane aluminium panels. The 2m height fitted 25 trays. Tomatoes were split into halves and placed in 50cm by 100cm stainless steel trays (mesh type) each with a holding capacity of about 7 kg. Roma tomatoes with a moisture content of 90% to 92 %(wb) were dried up to 10 %(wb) moisture content. A load of 4200 kg of fresh tomatoes was dried in 30 hours to a final weight of 400 kg. Air entered a 348.9kW heat exchanger at temperatures between 20°C to 35°C and entered the dryer at 55°C. The geothermal water with a mean flow rate of $25m^3/h$ entered the heat exchanger at a temperature of 59°C and exit at temperature between 51°C to 53°C.

The arrangement of the geothermal tomato dryer system is shown in Figure 2.11. Chilli and garlic have also been dried with waste heat recovery from a geothermal plant (Thiebrat *et al*., 1997). Geothermal water at about 80°C was circulated through a cross-flow heat exchanger by a 2 hp pump. The reported airflow from the heat exchanger to the drying chamber was 1kg/s. They claimed to have dried 450kg of chilli from 75% wb to 13% wb with an average air temperature of about 70°C and 220kg of garlic from 75% wb to 55% wb with an average air temperature of 50°C. The drying time was 46 hrs with a mass flow rate of hot water of 1kg/s for chili against a drying time 94 hours and a mass flow rate of hot water of 0.04kg/s for garlic.

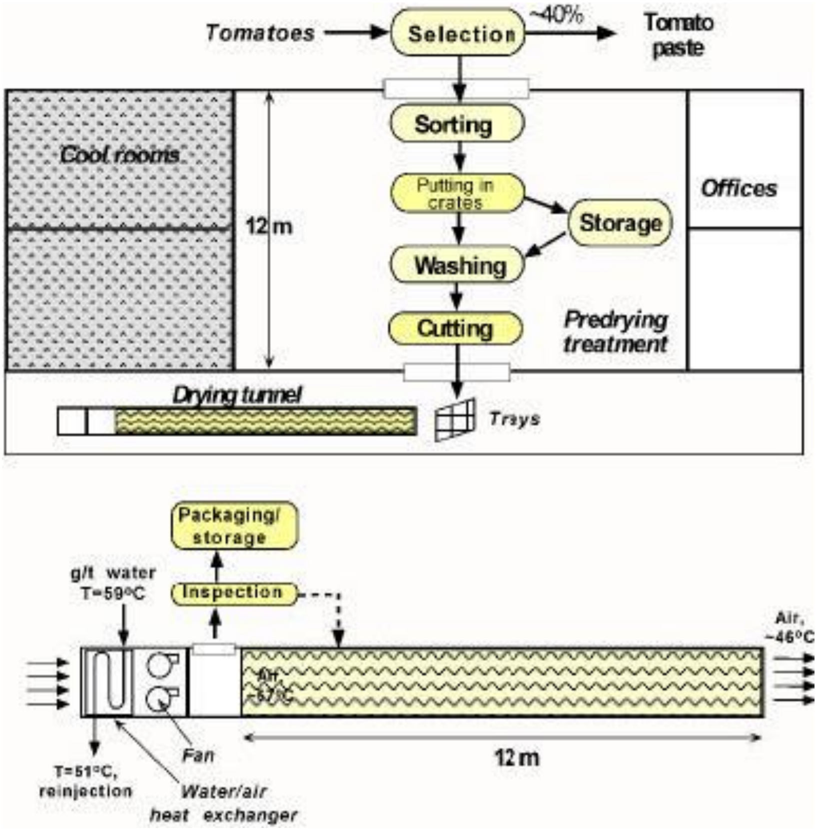


Figure 2.11: Schematic diagram of tomato dryer system (Andritsos ***et al***., 2003)

2.8 Energy storage technologies

Thermal storage can be integrated into a dryer to achieve fuel economy and ensure a continuous drying process. The most common thermal storage methods are sensible and latent heat (Dincer and Dost, 1996; Kaygusuz, 1999). Low-cost sensible heat storage materials include water and dry rocks in gravel form (Decher, 1994). Water is preferred to rocks due to its higher heat storage to volume ratio compared to that of rocks. Its major drawbacks are corrosion and leakage.

A Latent heat storage material stores and releases energy during a phase change at a desired temperature (Dincer and Dost, 1996). It requires a smaller mass but it tends to supercool and is more expensive compared to rock and water. Industrially sensible heat storage is achieved by use of fire tube and water tube boilers (GCCC, 1998). In fire-tube boilers, combustion gases flow through the tubes thereby heating the water that surrounding the tubes. In water-tube boilers, the water flows through the tubes and is heated by the gases of combustion that fill the furnace and heat the outside metal surfaces of the tubes. Water-tube boilers may be classified as natural circulation boilers or forced circulation boilers.

A research project funded by the Gas Research Institute (GRI) to determine what new technologies are applicable to heat exchangers that involve flue gases from combustion of natural gas found out that significant increase in the convective heat transfer coefficient could be achieved with the use of heat transfer enhancement devices (Bergles *et al.*, 1991). The study identified twisted-tape inserts as a potential heat transfer enhancement device for water heaters. Burners in fuel-fired water heaters are placed below the storage tank, with the flue extending up through the center of the tank through a draft hood. The combustion products enter the flue tube at a very high temperature (approximately 1215°C) and transfer heat by convection and radiation to the tube wall, and then by conduction to the water.

When a baffle, such as a flat plate, was inserted in the flue, increased heat transfer occurred from the hot combustion products to the flue wall. The increase in the heat transfer was even greater when a twisted baffle tape was inserted in the flue way of a water heater. The twisted tape augmented the convective heat transfer from the flue gases to the wall surfaces. In addition, the hot tape transferred heat to the water-tube walls by radiation. Beckermann and Goldschmidt (1986) investigated experimentally and empirically the effects of velocity of the flue gases, the twist (i.e. number of turns) of the tape, and the surface emissivities on the total heat transfer (convection and radiation) in a fuel-fired water heater. They reported that compared to an empty tube, the flue tube with twisted tape enhanced the overall heat transfer performance by as much as 50%. The improved flue baffle design is capable of increasing the recovery efficiency to about 80-85%, depending on the specific geometry. In this project, a copper twisted baffle tape was chosen to enhance overall heat transfer performance.

2.9 Hot water systems

Hot water systems may be classified based on type of expansion tank or water flow method. The two types falling under the expansion tank are “open tank” and “closed tank” system while those falling under water flow method are forced convection and gravity (thermosiphon).

2.9.1 Open tank system

In this arrangement, the increase in volume due expansion of the heated water is taken up by an expansion tank located above the highest point in the system, usually the attic. The expansion tank is open, with an overflow pipe at the top, so that if the tank becomes too full of water, it will flow out through the pipe and not over the side of the tank to the attic floor. The normal water temperature in an open system is approximately 82^oC.

2.9.2 Closed tank system

In a “closed” system the expansion tank is located at the base of the system, together with the boiler. The expansion tank has no overflow pipe but is completely airtight. When the water in the system expands, it compresses the air in the tank and puts the water in the entire system under pressure, making possible the maintenance of a higher water temperature usually well above 93^oC but without forming steam (Integrated Publishing, 2009).

2.9.3 Forced convection systems

Forced hot water systems use a water pump to circulate water from the boiler to the radiators in the rooms and back into the boiler. With forced hot water system the position of the radiator/heat exchanger relative to the boiler is irrelevant.

2.9.4 Thermosiphon/gravity hot water system

The circulation of water relies on the difference in density between the hot and cold water in the system. For space heating hot water systems, the radiator/heat exchangers must be placed above the boiler. When water is heated in the boiler, it rises up because it is lighter than the relatively colder water in the system piping. That cold water, in turn, falls back into the boiler (by gravity) and before long a Ferris wheel flow of hot water from the boiler to the radiators is set up. The flow rate of water depends on;

(i) The distance between the boiler and the radiator. The bigger the distance the faster the flow.

(ii) The size of the pipes. The larger the pipes, the faster the flow as the larger pipes offer less resistance to flow than smaller pipes.

(iii) The temperature difference between the supply and the return water. The hotter the water, the faster it circulates.

The head available forcing circulation through a radiator in a gravity system is proportional to the elevation of the radiator/heat exchanger element above the boiler, and the temperature difference between the flow and return pipes. The forcing pressures in self circulation system with operating temperatures between 50-95^{o}C are as shown in table C-1 of Appendix C (Engineering ToolBox, 2005). The thermo-siphon effect for hot water heating is also employed with solar water systems. In a thermo-siphon hot water system, the boiler is replaced with the solar collectors as the principal heating component while the storage tank must be located above the solar collector at about 60cm above the collector to avoid recirculation at night when the collector becomes cold (Gordes, 1982).

The heating of water in a solar water heater is achieved either through direct heating by the collector itself Huang and Shieh (1985) and Morison and Braun (1985) or indirectly via a heat exchanger (Parent *et al*., 1990). In both cases, the thermosiphon induced flow is a result of the incident solar radiation but is also affected by the hot water removal pattern. To maintain the temperature stratification, hot water is drawn for use from the very top of the tank (where it is hottest). This water is replaced by new cold water, which should enter at the very bottom.

2.10 Heat exchanger

A heat exchanger is a device built for efficient heat transfer from one fluid to another, whether the fluids are separated by a solid wall so that they never mix, or the fluids are directly contacted (Kakac and Liu, 2002).

2.11 Classification of heat exchangers

2.11.1 Parallel flow heat exchanger

In a parallel flow heat exchangers, two fluids of different temperature flow along the same axis in the same direction. A schematic diagram of a parallelflow heat exchanger is shown in Figure 2.12.

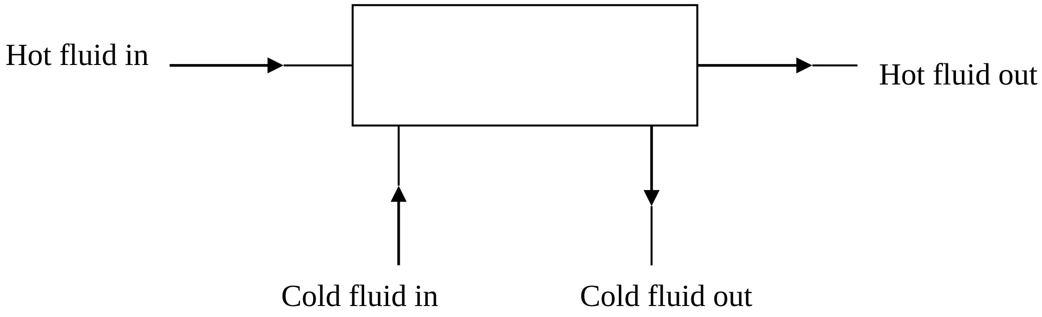


Figure 2.12: A typical arrangement of a parallel flow heat exchanger

2.11.2 Counter flow heat exchanger

In counter flow heat exchangers the fluids flow parallel to the same axis in opposite directions. A schematic diagram of a counterflow heat exchanger is shown in Figure 2.13.

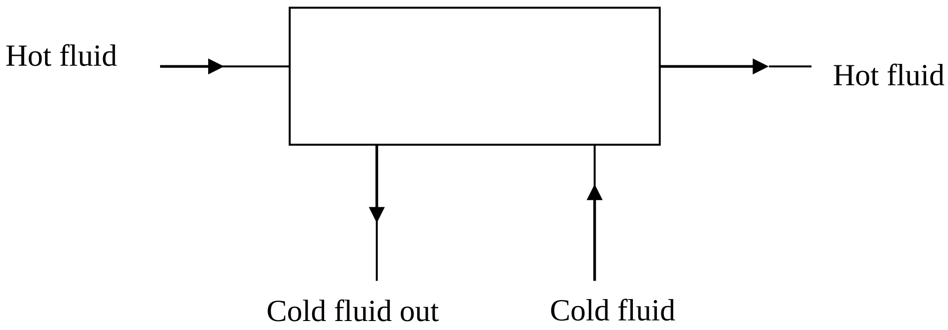


Figure 2.13: A typical arrangement of a counter flow heat exchanger

2.11.3 Cross flow heat eachanger

In a crossflow heat exchanger, the streams are normal to each other. Crossflow heat exchangers can further be classified as either single-pass or multi-pass. In a multi-pass cross flow type, one stream crosses back and forth through the path of the other flow. A stream may be mixed, flowing through a single passage, or unmixed in which it is broken up into many separate passages. One side can be mixed with other unmixed or both sides may be the same. Also the fluids are not necessarily the same e.g. one may be liquid and the other gas. Each configuration has advantages in different applications. The major advantage of crossflow heat exchanger over the others it can be made very compact, economizing on space and material, and that there is less difficulty in designing headers for two different streams. Schematic diagrams of a single-pass and multi-pass crossflow heat exchangers are shown in Figures 2.14 and 2.15.

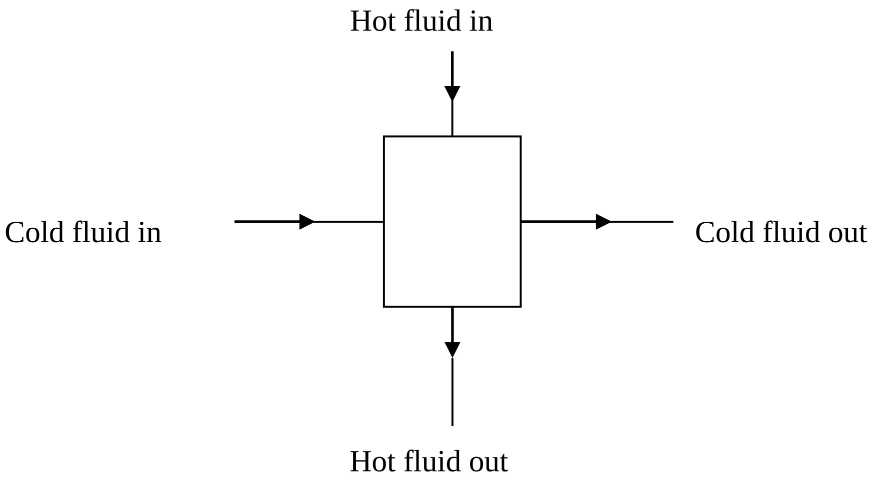


Figure 2.14 Single-pass crossflow arrangement

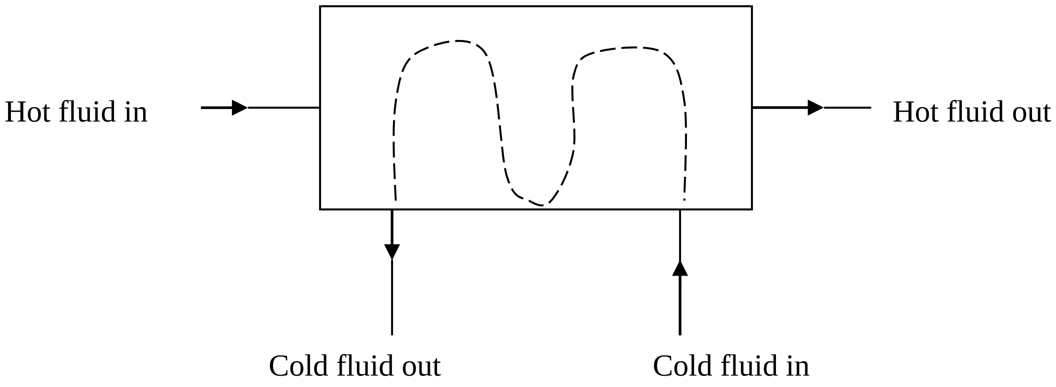


Figure 2.15 Multi-pass crossflow heat exchanger arrangement

The major disadvantage is that in general they have a very large drop in pressure for the flow transverse to the tubes for a given heat transfer rate (Fraas, 1988).

The common type of crossflow heat exchanger design is the shell-and-tube heat exchanger. It is built of tubes (round or rectangular) mounted in shells (cylindrical, rectangular). One fluid stream flows along the bunch of tubes and the other within the outer shell, parallel to the tubes, or in cross-flow. They provide relatively large ratios of heat transfer area to volume and can be easily cleaned. The more common tube arrays may be classified as either in-line or staggered.

These configurations are specified by the transverse spacing, the longitudinal spacing, the tube diameter, and the number of rows. The in-line tubes tend to give a somewhat lower pressure drop and poorer heat transfer because the flow tends to be channeled into high velocity regions in the centre of lanes between the tube rows. The staggered tubes, on the other hand, produce good mixing of the flow over the bank tube banks, but give a higher pressure drop. The pressure drop can be overcomed by forced draft but it is desirable to keep power consumption to a minimum especially as energy costs rise (Fraas, 1988).

Research has shown that where a heat exchanger comprises of several rows of tube banks, the turbulence induced by the front bank leads to a higher heat transfer coefficient for the second and subsequent banks than for the first. Therefore as the use of forced draft will lead to a further increase in turbulence on the first bank of tubes which will further enhance the heat transfer coefficient, the pumping work done by the fan will then be of value in improving the heat transfer over the subsequent banks, thus resulting to a high temperature of the drying air (Fraas, 1988). In this project, a crossflow heat exchanger design with tubes staggered in a triangular formation was chosen.

2.12 Heat exchanger systems for crop drying

Andritsos *et al*. (2003) reported the use of a finned-tube coil air-water heat exchanger for heating the drying air having a capacity of 300,000 kcal (348.9kW). Air entered the shell side of the heat exchanger at atmospheric conditions (20-35^{o}C) and exited at a temperature of 55^{o}C. The temperature of incoming geothermal water entered the finned tube coil at a temperature of 59^{o}Cand exited at a temperature between 51-53^{o}C.

Mastekbayeva *et al*. (1998) reported the use of a flue gas-to-air cross-flow type shell and tube heat exchanger. The heat exchanger was designed to transfer heat from the flue gas to the process air entering the heat exchanger by forced draft. The flue gases generated from the combustion of rice husk briquettes in a biomass stove were channelled to eight galvanised pipes of outer and inner diameter of 50mm and 44mm respectively via a chimney. The process air was on the shell side. The arrangement of the tubes in the heat exchanger is as shown in Figure 2.16. The design inlet and outlet temperatures of the flue gas were taken to be

600^{o}C and 300^{o}C respectively while that of the outlet to the heat exchanger was 60^{o}C.

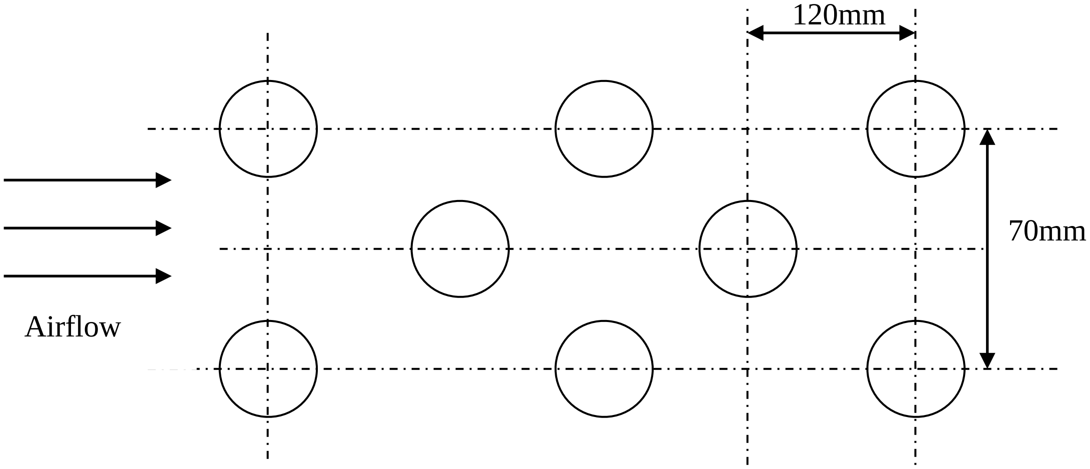


Figure 2.16 Arrangement of tubes in the heat exchanger (Mastekbayeva *et al*., 1998)

2.13 Economics analysis of a dryer

2.13.1 Introduction

Economic and financial considerations are important factors to be considered when examining and evaluating the viability of nay investment. The payback period of a system is important because if it is low; people will come forward to procure the system. However, even if there is substantial long term savings, the user will be hesitant to install the system if the payback period is long.

2.13.2 Annualized cost method

Kalbande and Jadhev (2007) and Sreekumar et *al*. (2008) have reported the use of annualized cost method. In this method, the annualized cost of the dryer was calculated using the annualized cost method, and this cost was divided by the amount of the product dried per year to obtain the cost of drying per unit weight of dried product.

2.13.3 Life cycle analysis and payback methods

Singh **et *al***. (2006) and Sreekumar **et *al***. (2008) have reported the use of Life cycle saving and payback period methods. They first calculated the total annual savings per year for the dryer in the base year. Then, the present worth of the annual savings over the life of the systems as well as the cumulative present worth of the annual savings and net present value were calculated. The internal rate of return (IRR) was also calculated. Finally the payback period method was applied to the life cycle savings to determine the payback period.

2.14 Efficiency of dryers

Energy efficiency in drying is important as energy consumption is such a large component of drying costs. They are useful when assessing the performance of a dryer, looking for improvements, and in making comparisons between the various classes of dryers which may be alternatives for a particular drying operation. Basically, it is a ratio of the minimum energy needed to the energy actually consumed. But because of the complex relationships of the food, the water, and the drying medium which is often air, a number of efficiency measures can be worked out, each appropriate to the circumstances and therefore selectable to bring out special features important in the particular process (Earlie, 1983).

Heat has to be supplied to separate the water from the food. The minimum quantity of heat that will remove the required water is that needed to supply the latent heat of evaporation, so one measure of the efficiency is the ratio of that minimum to the energy actually provided for the process. Sensible heat can also be added to the minimum, as this added heat in the food often cannot be economically recovered.

Yet another useful measure for air drying such as in spray dryers, is to look at a heat balance over the air, treating the dryer as adiabatic with no exchange of heat with the surroundings. Then the useful heat transferred to the food for its drying corresponds to the drop in temperature in the drying air, and the heat which has to be supplied corresponds to the rise of temperature of the air in the air heater. So this adiabatic air-drying efficiency, $\boldsymbol{\eta}$ can be defined by:

$$\boldsymbol{\eta = (T_1 - T_2)/ (T_1 - T_a)}$$

2.15 Summary of major findings in literature review

2.15.1 Lessons learnt

A range of crop drying technologies which include electric powered dryers, fossil fuel dryers, ambient drying, sun drying, solar drying, geothermal energy recovery drying, solar-biomass and solar-fossil fuel hybrid dryers have been discussed. Electric dryers have been found to have high operation costs. Fossil fuel powered dryers have high operational costs and may pollute the produce with exhaust fumes. However, LPG is said to be non-toxic. Ambient drying, though economical, prolongs the drying period. Although sun drying is cheapest method in terms of construction, large scale sun drying requires an extensive drying ground and the quality of the dried products is poor due to contamination of the product by insects, dirt, rain and discolouration due to ultra-violet radiation.

Solar dryers shortens the drying process and produces a better quality product compared to open sun drying but like open sun drying, it is dependent on local weather condition and is therefore unreliable. Hybrid driers have been found necessary to ensure continuity of the drying process leading to high quality of the dried products. Solar-biomass hybrids technologies incorporating biomass as a secondary heat source for drying has been explored. However, excessive use of biomass will lead to loss of biodiversity. In addition, all these hybrid technologies involved direct combustion of the biomass material into ash. The flue gas heated the drying air through a heat exchanger before exiting at high temperatures of about 300^{o}C.

Geothermal waste water heat recovery crop dryers have been used to dry tomatoes and chilli. However, geothermal energy is a localized resource. The use of geothermal waste water has shown that heat energy stored in water can be recovered via a heat exchanger to dry crops. Also sensible thermal storage using water as the storage medium was found to be the most feasible in terms of cost. Several hot water systems have been explored with “open” tank preferred to “closed” tank since it does not operate at high pressure and temperatures and therefore low chances of risks involved.

Gravity hot water systems were found to be economical since they don’t require a water pump for circulating the in the system. Various designs of heat exchangers have also been discussed. An air-water finned-tube coil heat exchanger and an air to air tube and shell cross flow heat exchanger have been used in drying crops. A major advantage of cross-flow heat exchanger over others is that it can be made very compact, economizing on space and material, and that there is less difficulty in designing headers for two different streams.

Natural convection dryers have advantages over forced convection solar drying due to lower investment, operation and maintenance costs. They are however limited due to their small holding capacity and inadequate rate of moisture removal making them unsuitable for small scale industrial production of fruits, vegetables, spices, fish and medicinal and herbal plants. Forced convection systems using fan operated either by grid connected electricity or solar module have been used to dry crops.

The drying air can either be made to pass through the product (tray type vertical dryer with air exiting at the top) or over the product (tunnel type dryer with air exiting at the side). In vertical systems, several trays can be stacked over one another thus economizing on the drying space but there is risk of moisture condensation on the top tray since the air above the crop bed is not substantially different in temperature from that of ambient air. A tunnel type forced convection dryer was found to be economical in terms power requirement to drive a fans since the air passed over the products. The recommended physical properties of drying air for most foods are a temperature of (50-57^{o}C), relative humidity (10-20%) and a velocity (0.1-1.2 m/s). To avoid growth of moulds on the product, the relative humidity of exit air should be limited to 75%.

2.15.2 Way forward

None of the investigators reviewed have studied the performance of a dryer using portable water as thermal energy storage. Therefore a liquefied petroleum gas powered dryer with portable water as a medium for thermal storage was proposed. In this project, an experimental LPG dryer was developed. LPG was chosen since is nontoxic and safe around food materials and can easily be substituted with biogas in future projects. The thermal storage system comprised of an “open” tank thermosiphon/gravity system. The system recovered heat from combustion flue gas and store it in water. During the drying process, the stored energy would be recovered through a cross-flow heat exchanger.

The design of the drying chamber was to incorporate both tray and tunnel type features in order to take the advantage of the stacking of trays (tray type feature) and passing air over the product (tunnel type feature) to minimize on both space and power requirement of the fan. The air was to pass over the product rather than through the wet crop bed and thus minimizing the risk of water condensation. A PV/ battery electrical system to drive the fans was to be incorporated. This would make the dryer to be acceptable for use in rural areas not connected to the grid.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

A thermosyphon heat recovery system with a cross-flow single-pass shell and tube heat exchanger was designed, constructed and set up at the Appropriate Technology workshop of Kenyatta University, Nairobi, Kenya. The system recovered heat from exhaust flue gas resulting from the combustion of liquefied petroleum gas (LPG) passing through a twisted copper strip fitted inside the 10.16cm internal diameter galvanised iron flue pipe. Heat was applied to the boiler from a framed 3-ring LPG burner MODEL GB07 made in China with a thermal rating of 30MJ/hr. Naturally occurring convective currents lifted the heated water from the bottom of the boiler to the heat exchanger and back to the bottom of the boiler. At the heat exchanger sensible thermal energy stored in the water was conducted across the heat exchanger tube walls into the heat exchanger shell. One 12VDC, 48W fan forced ambient air across the heat exchanger vertical tubes while another 12V DC, 36W fan sucked the heated air into the drying chamber. In the horizontal plane, the heat exchanger and the boiler were designed to be as close as possible in order to minimize the length of the pipe work and heat losses. In the vertical plane, the heat exchanger was positioned such that the cooled water takeoff point on the descending pipe was 60cm above the boiler’s hot water rises takeoff point. The complete system was mounted on a metallic structure 180cm high as shown in Figure 3.1.

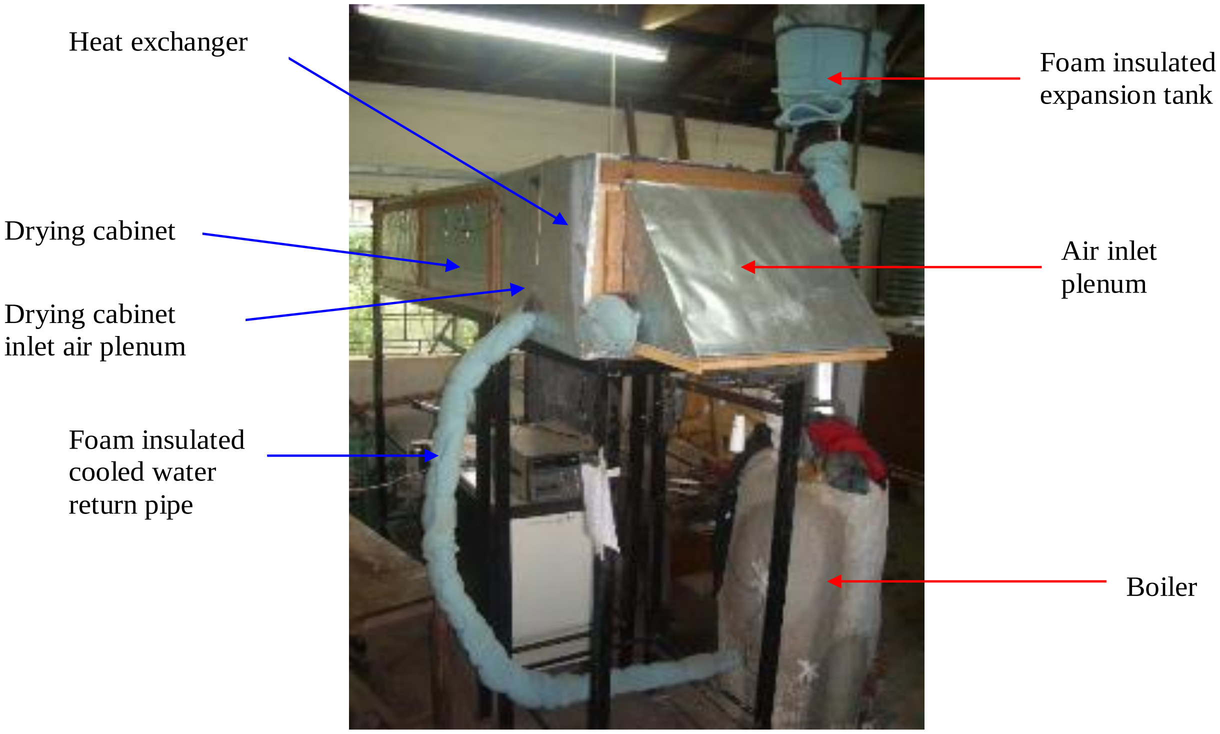


Figure 3.1 Components of the drying system

3.2 Design procedure

In designing the system the following procedure was followed;

(i) A load of 100kg of fresh tomatoes was assumed.

(ii) Mass of water to be expelled from 100kg of tomatoes was estimated (Excell, 1980) and found to be 93.62kg.

(iii) Taking the heat of vaporization of water at 1 atmosphere as 2.257 MJ/kg, the heat needed to remove 93.62kg of water was calculated to be 211.3 MJ (58.69 kWh). Also assuming a drying temperature of 55^{o}C and specific heat capacity of tomatoes as 3.98KJ/kg^{o}C, the heat required to raise the temperature of the tomatoes in the chamber from room temperature of 15^{o}C to 55^{o}C was calculated to be 15.92 MJ (4.42 kWh). Thus total heat required to dry 100kg of tomatoes was estimated to be 227.22 MJ (63.11kWh). A boiler/storage system of 637 litres was required to store the required heat energy. However, the thermal mass of the of the boiler, heat exchanger and the pipe work all which were made of galvanised iron, would also absorb and store heat energy, and therefore the mass requirement of water was to be less. Also, only part of the drying duration was to depend on the thermal storage alone, while the initial drying period was to take place with the burner ON. As a result of the two considerations, a 225 litre storage water heater was chosen. The total volume of the water in the system was about 300 litres (including the heat exchanger, expansion tank, the hot water riser and cold water return pipe).

(iv) The temperature and relative humidity of ambient air entering the heat exchanger were assumed to be 15^{o}C (db) and 90% respectively. The temperature of air leaving the heat exchanger was assumed to be 55^{o}C. Using psychrometric chart, the humidity (mixing ratio) ratio and the relative humidity of heat exchanger exit air were obtained as 0.0096kg water/kg dry air and 9.7% respectively. Assuming a relative humidity of drying chamber exit air as 75%, the corresponding dry bulb temperature and humidity ratio were obtained as 30^{o}C and 0.0202kg of water/kg of dry air respectively. The increase in humidity ratio of the drying air was calculated to be 0.0106kg of water/kg of dry air. The total mass and volume of dry air required by 93.62kg of water were calculated to be 8832.1kg and 7581.92m^3 respectively.

(v) Using the volume of air determined in (iv) above and assuming a drying period of 12hours, the volumetric airflow and CFM requirement of the fan were calculated to be 0.176 m^3/s and 370.8 CFM respectively.

(vi) The battery bank and solar panel size were designed based on their ability to power 6 fans Model AFB1212SH from Delta electronics of China for 12 hours. From the manufactures data, the fans had a voltage and current rating of 12V and 0.9A respectively and a volumetric airflow of (0.053 m^3/s) or 113.11CFM. The battery and solar panel size were 90Ah and 97.24W respectively.

(vii) In designing the heat exchanger, the temperatures of the water entering and exiting the heat exchanger were assumed to be 60^{o}C and 50^{o}C. The temperatures of the air entering and exiting the heat were assumed to be 15^{o}C and 55^{o}C. From the conservation of the total mass the total heat transfer between the two streams can be was expressed as;

$Q = m_w C_{pw} (T_{w,in} - T_{w,out}) = m_a C_{pa} (T_{a,out} - T_{a,in}) = UA\Delta T_{lm}F$

The heat flow "q" was calculated as 8.21kW. A minimum number of 48 heat exchanger riser tubes of internal diameter 2.54cm were determined.

(viii) With the average hot water flow out of the boiler and cooled return water temperatures back to the boiler taken as 60°C and 50°C respectively and using Table A-7 in Appendix A, the circulating pressure was found to be 39 N/m^2.

(ix) About 7kgs of quartered tomatoes fitted a 100cm by 50cm (0.5m^2) drying tray ((Andritsos, *et al*., 2003). Therefore, 100 kg of tomatoes would occupy 7.14m^2. By limiting the width, length and height of the drying chamber to 0.7m and 2m and 0.40m respectively the number of drying trays was calculated to be 5. However, the actual load of tomatoes that would fit the 5 trays was dependent on the geometry of the tomato load.

3.3 Components of the heating system

The heating system components consisted of a water boiler made from a 50-gallon (225 litres) hot water storage tank, a framed 3 ring LPG burner MODEL GB07 made in China rated at 30MJ/hr and an LPG cylinder fitted with a regulator rated at 1.5kg/h connected to an 8mm inside diameter hose linking the regulator and the burner.

3.3.1 Construction of the boiler

The schematic design of the boiler is shown in Figure 3.2. It had the form of a single flue gas storage water systemwas constructed from a galvanised iron tank commonly used in domestic hot water systems The tank was purchased from M/S JANTECH ENGINEERING LTD, a local manufacturer based in Nairobi, Kenya. From the manufactures data, the tank was made of 14gauge (2mm) galvanised iron sheet with a water holding capacity of 225 litres and could withstand a pressure tested to 4bar. The diameter and height of the tank were 63.5cm and 109.2cm respectively. A photograph of the tank is shown in Figure 3.3.

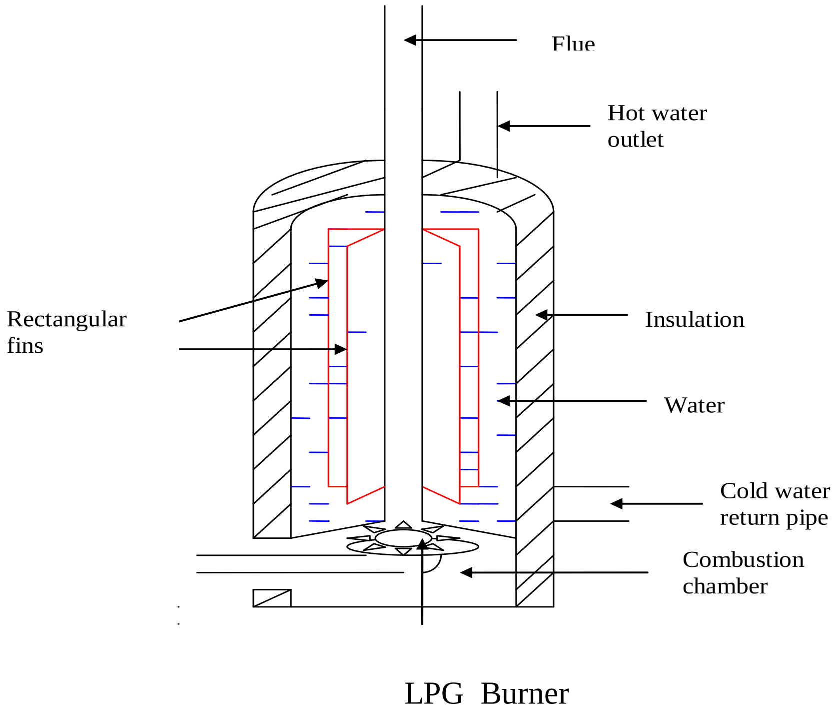


Figure 3.2 A schematic design of the boiler system

Figure 3.3 A 50 gallon (225 litre) hot water storage tank

Two coinciding 10cm diameter holes one at the bottom and the other at the top plate of the water heater cylinder were cut. The tank was then cut along the diameter just near the top resulting into an open drum and a pan as shown in Figure 3.4.

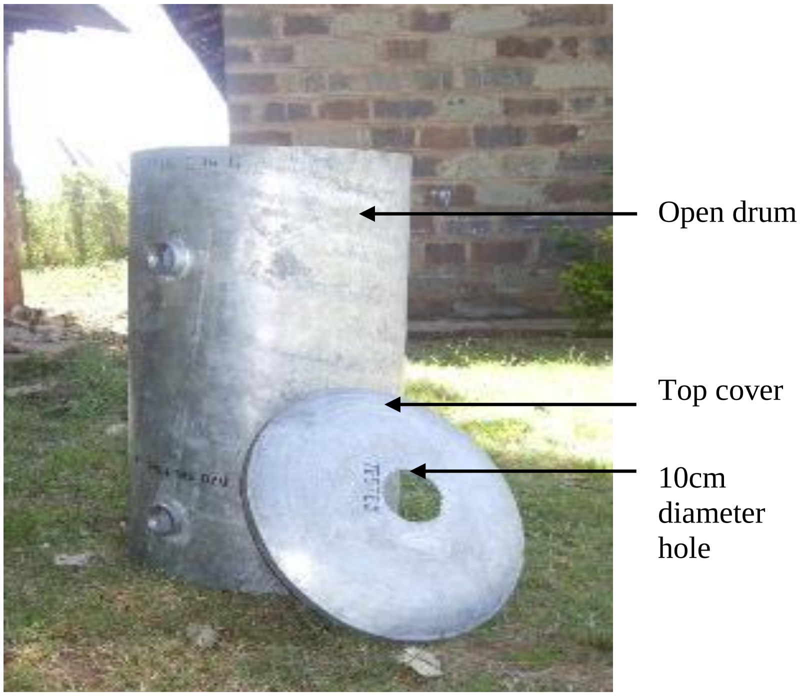


Figure 3.4 Storage tank with its top section removed

A 10.16cm diameter GI pipe was used as a flue pipe. In order to enhance heat transfer from the inner surface of the flue pipe to the water, five pieces of stainless steel sheets measuring 50 by 76cm were welded lengthwise onto the galvanized iron pipe. Stainless steel was chosen due to its ability to withstand corrosion and also since it was readily available from the workshop. The dimensions of the stainless sheet were dictated by the space between the 10.16cm and the inner walls of the storage tank. A photograph of the finned flue pipe is shown in Figure 3.5

Figure 3.5 Flue pipe finned with stainless steel sheets

To enhance heat recovery from the hot flue gases before exhausting to the atmosphere, two thin twisted helical cooper strips measuring (0.16cm thick and 10cm wide) were inserted in the flue pipe and welded to the bottom and top edges of the flue pipe. Copper was chosen due to its high thermal conductivity (Table A-7 in Appendix A) and was readily available in the workshop. There was a small clearance between the twisted tape and the walls of the flue pipe tube to allow for easy insertion. Figure 3.6 shows a schematic of the twisted copper strip inside the flue pipe.

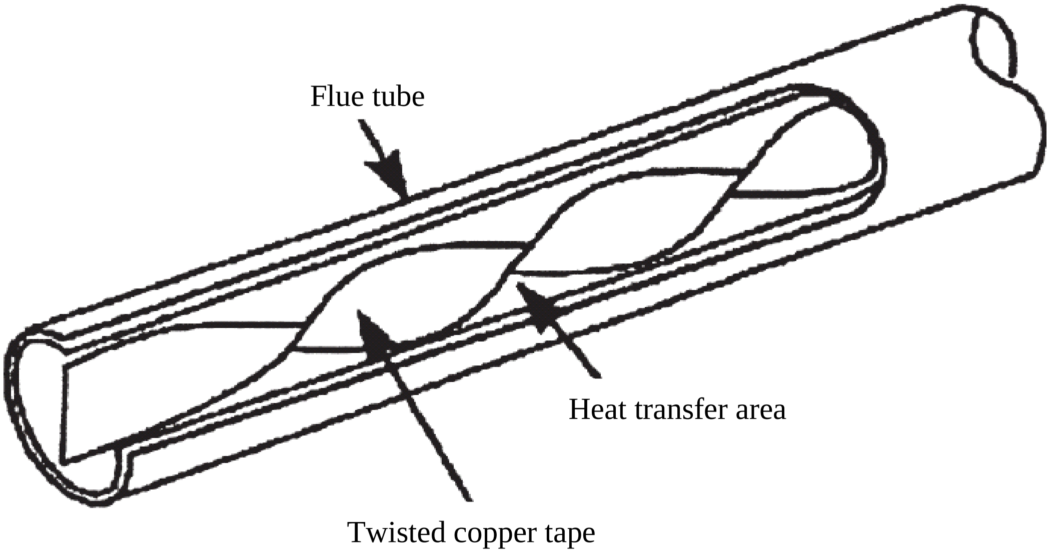


Figure 3.6 The appearance of the inner side of the flue pipe when fitted with a twisted helical copper strip

The finned 10.16cm flue pipe was placed inside the open tank and the bottom end aligned flush with the edges of the bottom hole and welded. The upper end of the finned tube was pushed through the hole on the saucer like piece. The tank was the aligned along the cutting line and welded. The flue tube was finally welded along the edges of the top hole leaving a protruding 30cm long piece of the pipe for connection to the external flue pipe. Five angle-iron pieces of 12.5cm were welded around the bottom of the storage tank to act as supports for the boiler above the LPG burner. A galvanised iron sheet 2mm thick by 12.5cm wide was then welded around the angle-iron stands on the outer side to form the combustion chamber, leaving one rectangular open door for inserting the LPG burner as shown in Figure 3.7.

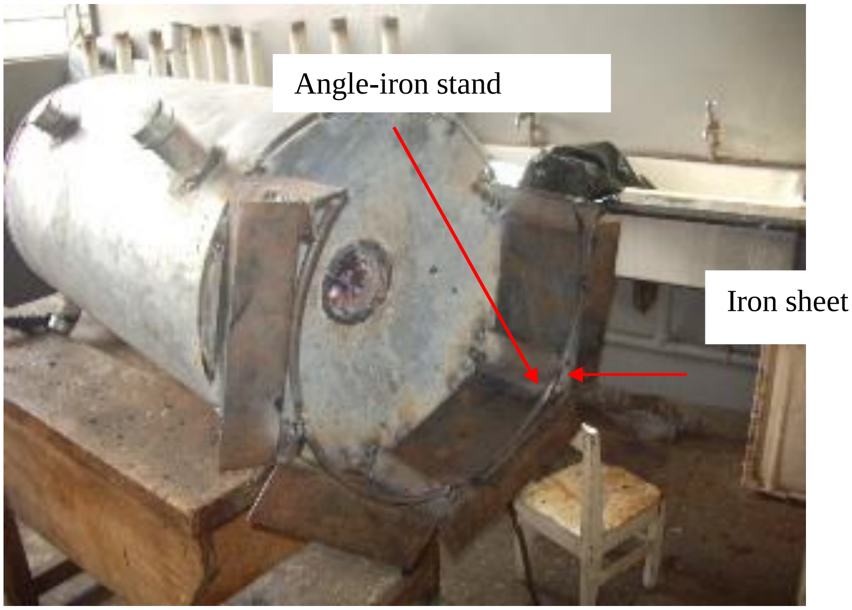


Figure 3.7 Details of the combustion chamber

To minimize heat loss the boiler, it was necessary to cover it with insulation. The materials considered were vermiculite, waste blanket materials and plaster of paris, which were all readily available locally. Vermiculite was readily available in the workshop and had earlier been obtained from Athi River, 30km South of Nairobi, Kenya. Kenyan vermiculite is reported to have been tested at the Institute of Occupational Medicine, Edinburgh, where no hazardous asbestos fibres were detected and thus it was safe to handle (Thermica Limited, 2004). Plaster of Paris was purchased from shops dealing with building materials while the waste blanket materials were purchased from M/S Spin and Spinners (a garment factory) situated in Ruiru Township, 25km East of Nairobi, Kenya. Since it was desirable that the water boiler be portable, it was necessary to use low density materials without compromising on the effectiveness of the insulation. Other factors considered in selecting the insulating materials included thermal insulating properties, thermal conductivity as well as rigidity after curing. Although vermiculite was denser (64-160kg/m^3) and had a higher thermal conductivity of (0.0633-0.0738 W/m^{o}C) (Norman, 1984) compared to 0.04W/m^{o}C of blanket materials respectively it had the highest thermal properties withstanding up to 1,100^{o}C (Thermica Limited, 2004), and thus was best suited to insulate the metallic surface of the storage tank whose temperature was expected to rise during heating. However its thickness was limited to 2.5cm in order to limit the weight and heat flow from the metallic surface outwards. Plaster of Paris is known for providing a hard and smooth surface after curing and thus was selected for outer insulation. This left the woollen blanket materials was chosen for the middle insulation layer.

Before insulating the tank, it was covered with a layer of chicken wire as shown in Figure 3.8. This was to support the impending layer of vermiculite- cement plaster. In general, the storage tank was insulated with a composite wall comprising of a 2.5cm layer of vermiculite covering as shown in Figure 3.9.

Figure 3.8 An un-insulated boiler covered with a layer of chicken wire

Figure 3.9 Boiler insulated with a layer of vermiculite

The vermiculite layer was in turn covered with 5cm layer of factory waste woollen blanket materials as shown in Fig 3.10 and finally with a 2.5cm plaster of Paris as shown in Figure 3.11.

Figure 3.10 Boiler insulated with woollen blanket materials above vermiculite

Figure 3.11 Complete boiler –storage system with a layer of Plaster of Paris above woollen blanket insulation

A framed 3 ring LPG burner MODEL GB07 made in China with a thermal rating of 30MJ/hr shown in Figure 3.12 for heating the boiler.

Figure 3.12 LPG burner MODEL GB07 made in China

3.3.2 Construction of the heat exchanger

A single pass cross-flow heat exchanger was designed as shown in Appendix B. The selection of pipes for use as risers was based on the fact that the smallest recommended internal diameter for gravity circulation systems is 28mm. Five identical radiator panels each consisting of two 0.038m internal diameter sub-headers and fourteen 0.025m internal diameter finned risers between them were constructed by brazing the open ends of the risers into holes made on the headers. The design of the radiator panel is shown in Figure 3.13.

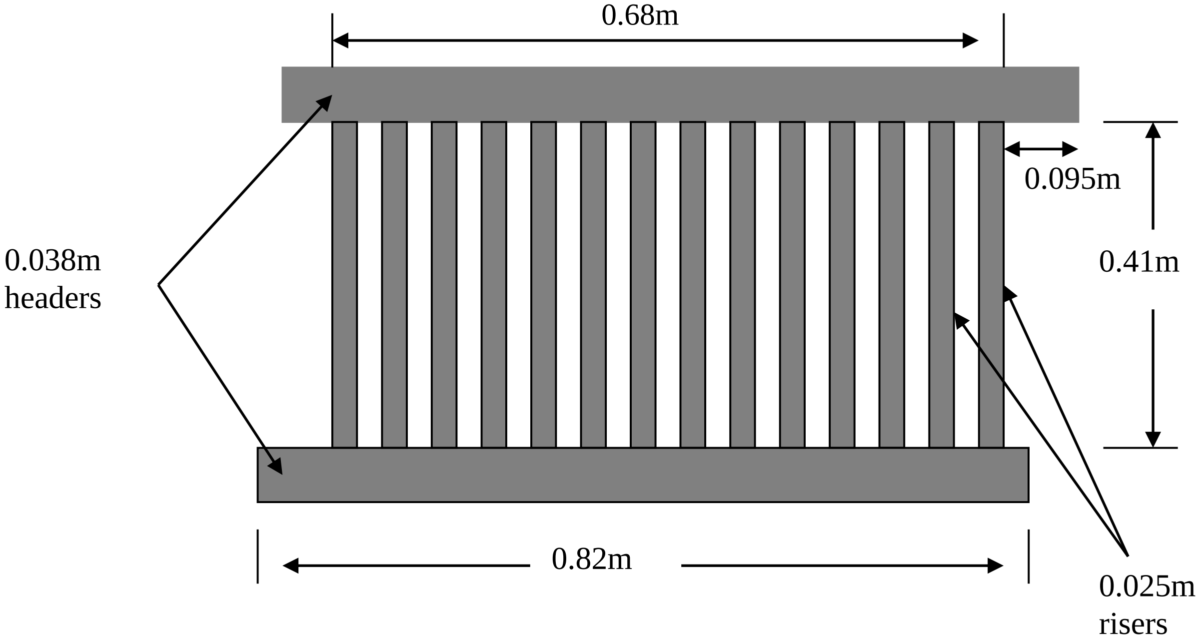


Figure 3.13 Design of the radiator panel

The radiator panels were then arranged such that the 0.025m risers within the heat exchanger assembly formed a staggered triangular formation of transverse and longitudinal pitch shown in Figure.3.14. A triangular pitch arrangement was chosen as it allows for the packing of more tubes into a given space while a staggered tubes arrangement was chosen as it produces good mixing of the flow over the tube banks resulting to a higher heat transfer (Fraas, 1988).

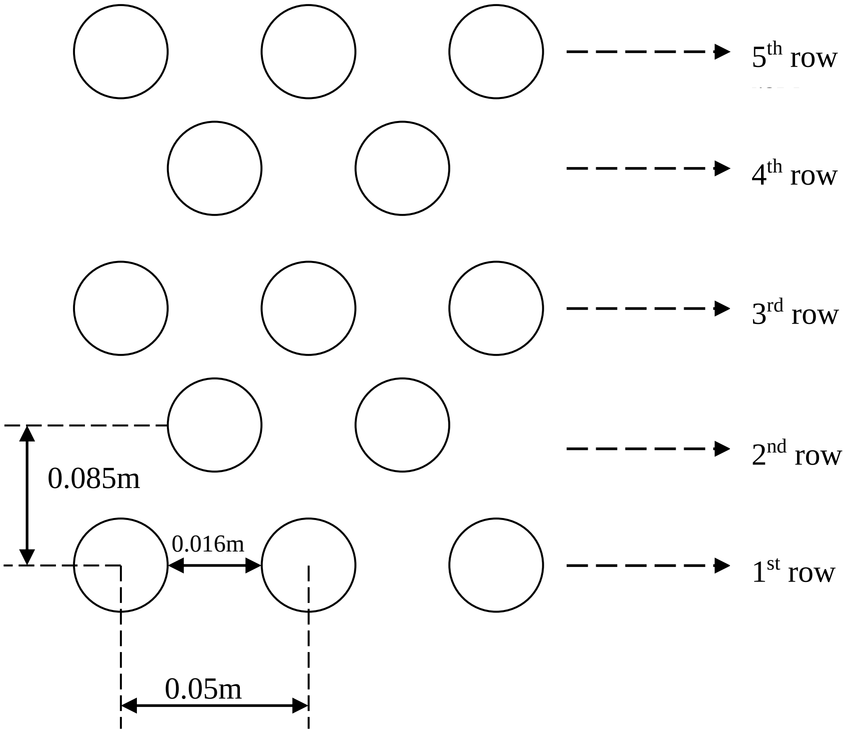


Figure 3.14 Arrangement of risers within the shell of the heat exchanger. Each row consisted of 14 risers giving a total of 72 risers

This arrangement gave rise to two sets of five 0.038m diameter parallel sub-headers with one set at the top and the other at the bottom. The diagonally opposite ends the two sets of parallel headers were corked by welding a 2mm thick piece of galvanized iron while the remaining ends opposite ends were brazed onto 0.051m main headers as shown in Figure 3.15.

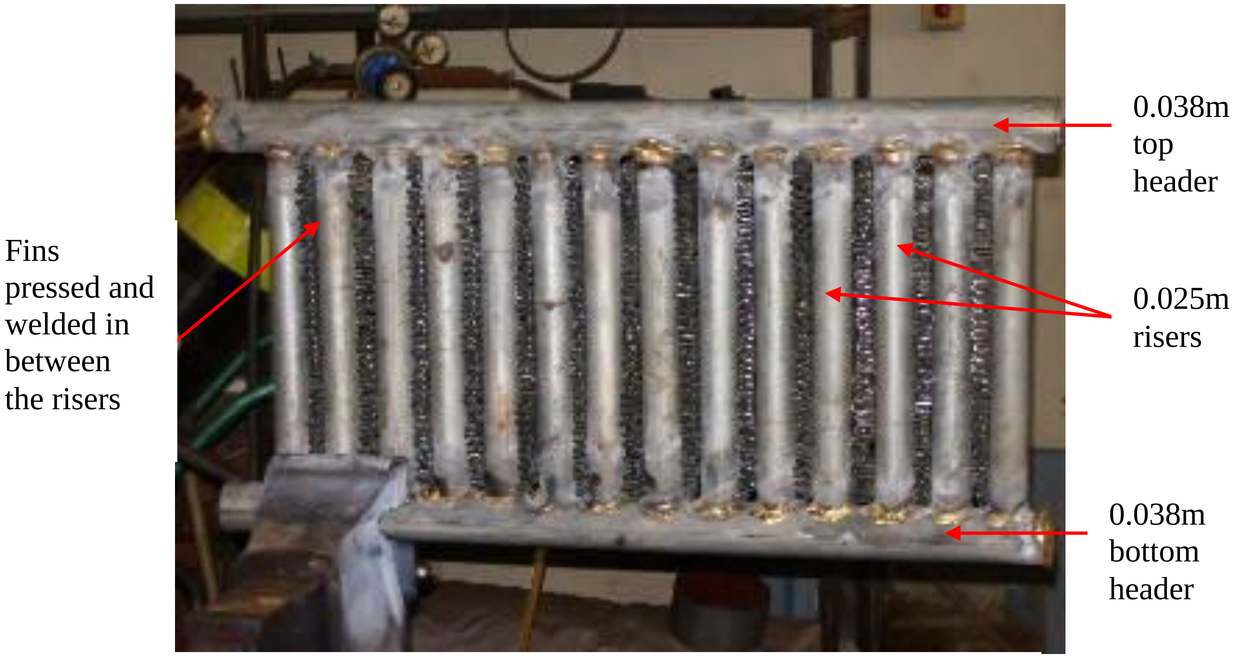


Figure 3.15 A complete radiator panel with fins between adjacent

The open ends of the sub headers were aligned with holes which had been drilled on the main top and bottom headers and then welded. Two of the diagonally opposite ends of the two 0.051m main headers were corked with 0.051m diameter external corks. During the assembly of the system, the open end of the top 0.051m main header was connected to the 0.051m hot water riser while the bottom one was connected 0.051m cooled water return pipe. Figure 3.16 shows a photograph of the complete heat exchanger.

Figure 3.16 Pictorial view of the complete heat exchanger

3.3.3 Expansion tank

Water expands by 4.2% when its temperature is raised from 4°C to 100°C. Therefore an expansion tank to accommodate the increased volume was a must. A 45 litre storage water heater whose bottom cover had been removed and was readily available in the workshop was used. Its 0.0254m terminal for hot water riser connection was removed and replaced with a 0.051m terminal for connection to the 0.051m hot water riser. An open expansion tank system was used. so as to avoid building up of high pressure in the system. Excessive pressure would discharge through the open bottom to the atmosphere and thus the boiler didn’t require a pressure-relief valve. It is a requirement that the open expansion tank be mounted at the highest point in the system and therefore the open tank was placed about 0.03m above the heat exchanger.

3.4 Construction of the drying chamber

The design of drying chamber is described in Appendix C. It was a 2m long, 0.8m wide and 0.53m high rectangular double walled tunnel fabricated from 0.04 by 0.04m timber. It consisted of two compartments each with a double layered access door fitted on the front side for easy loading and unloading of the product. Each compartment accommodated 5 drying trays stacked vertically. A sketch of the drying chamber is as shown in Figure 3.17.

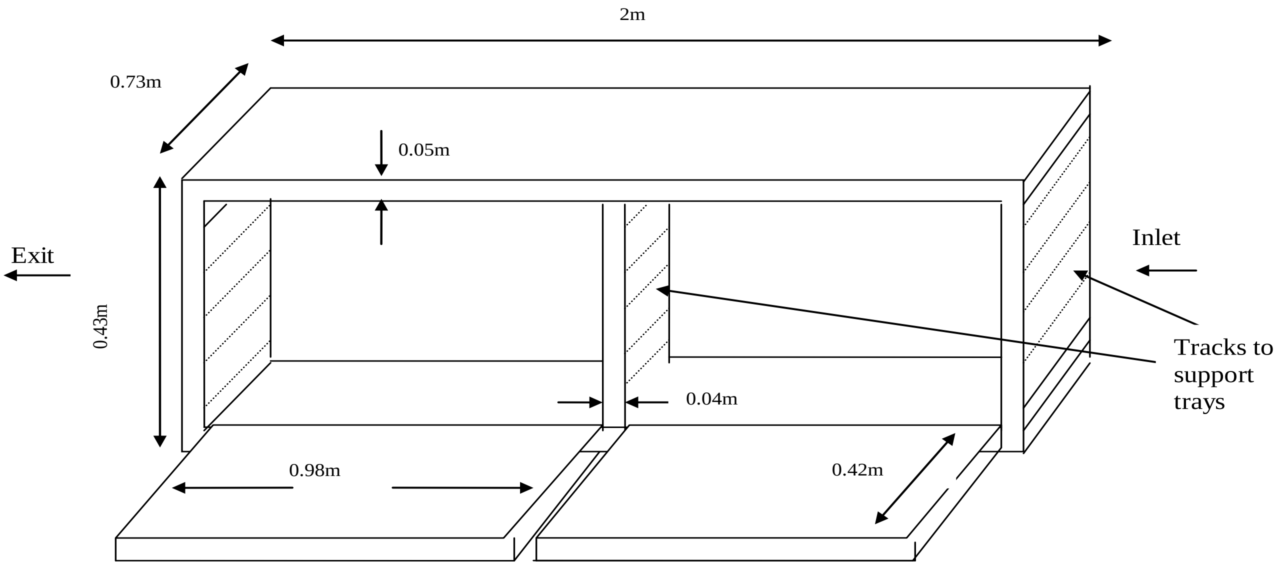


Figure 3.17 Schematic design of the drying chamber

The drying chamber was constructed by first making a rectangular framework from 0.04 by 0.04m timber as shown in Figure 3.18. All the inner walls of the wooden framework except the one for fitting the access doors were lined with 3mm plywood and then with aluminium sheet. For every inner wall covered with

Figure 3.18 Rectangular wooden framework for the construction of the drying chamber

plywood, a rectangular space with a depth of 4cm (thickness of the framework) was developed on the outer wall. This space was packed with waste blanket insulation to suppress heat losses and then covered with 6mm plywood. The outer walls of the drying chamber were then lined with galvanised iron sheet. The construction details of the access doors were similar to those of the walls of the drying cabinet. At the entry, centre and exit positions of the drying chamber a set of five grooved wooden tracks stacked one above the other were fitted for supporting the drying trays. The clearance between the inner side of bottom wall of the cabinet and the first track as well as the inner of the top wall of the cabinet and last track for all the three positions was 6cm while the spacing between two adjacent tracks was 7cm.

This ensured that corresponding tracks at all the three positions and hence the drying trays in both compartments were at the same level so as to avoid obstruction of air flow during the drying process. The constructed drying chamber is shown in Figure 3.19. Ten drying trays each measuring 0.63m wide x 0.9m long were made by attaching a coffee tray wire mesh to the bottom of the tray's wooden frame work. The drying area for each tray was 0.57m^2. The total drying area of each compartment was 0.57 x 5 = 2.85 m^2 while the overall drying area was 2.85 m^2 x 2 = 5.7 m^2.

Figure 3.19 Pictorial view of the constructed drying chamber

3.5 Construction of the air handling unit

The system had two air handling units, one at the ambient air intake side operating on forced mode and the other at the heat exchanger exit air side operating on induced draft mode. The ambient air intake side was triangular in shape to apparently incline the heat exchanger at an angle with respect to the inlet duct. The aim was to make the inlet-face area considerably greater than that of the inlet duct so as to reduce the pumping power losses (Fraas, 1988). The arrangement of the air unit is shown in Figure 3.20.

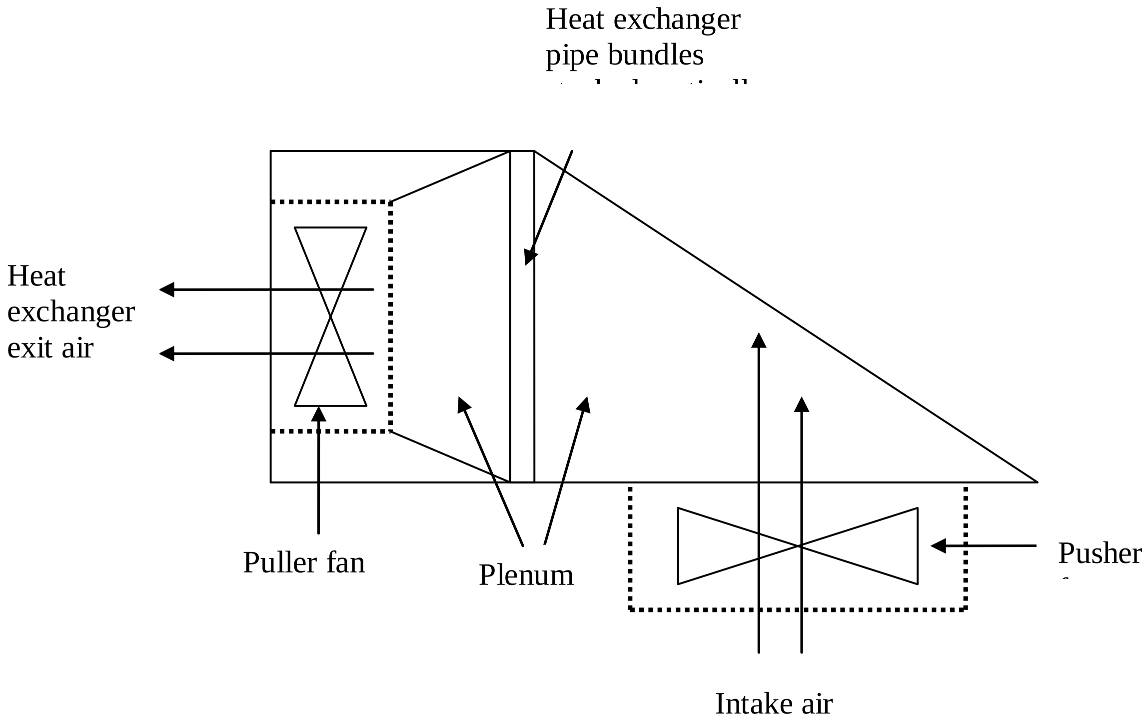


Figure 3.20 Arrangement of air handling unit

The ambient air intake side was equipped with a pusher fan model DENSO part number 065000-2521 widely used in the air condition system of small Toyota motor vehicles while the heat exchanger exit air side was fitted with a radiator cooling (puller) fan also used in small Toyota motor vehicles. Both fans were driven by solar/battery 12 VDC supply. The rating of both fans ranged between 1100CFM on low and 1850CFM on high.

3.6 Design of solar PV electric system

The main components of the electric system were two 50W solar panels, a 200Ah solar battery. The auxiliary components included one 12A solar charge controller, one voltmeter, one ammeter, 10 metres of 2.5mm^2 electrical cable, one double socket and two top plugs. All the components were arranged as shown in Figure 3.21.

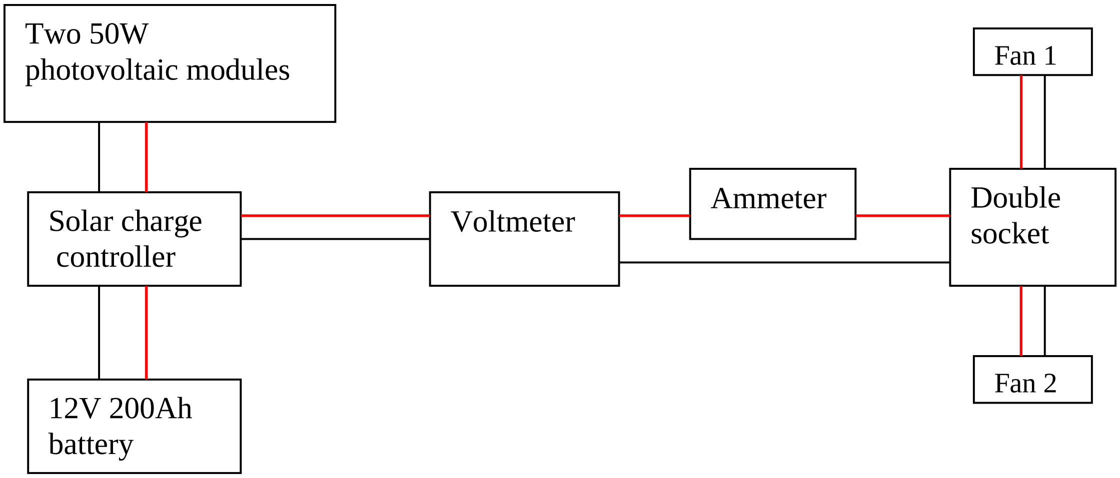


Figure 3.21 Schematic design of solar PV electric system

The purposes of the solar panels was to charge the battery and were mounted on the roof of the workshop building free from shadows as shown in Figure 3.22.

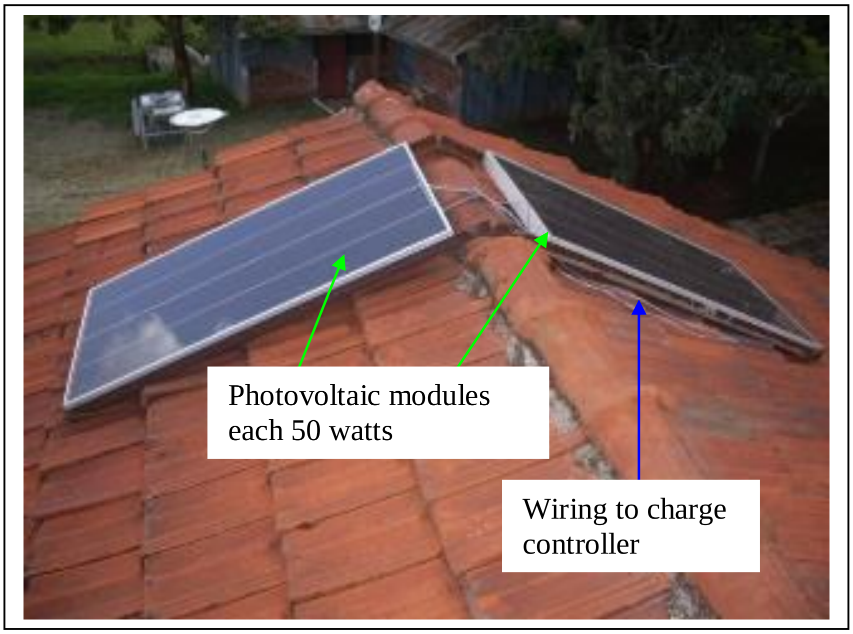


Figure 3.22 Two 50W photovoltaic modules on the rooftop

The battery was meant to store the electrical power obtained from the solar panels and were located in the workshop. The solar charge controller acted as an interface between the solar panel and the battery and between the battery and the electrical load. Its purpose was to monitor the level of the charge in the battery and to electrically disconnect the solar panel if the battery was fully charged or to electrically disconnect the load (fans) if the battery voltage dropped to a set reference value. This would prevent the battery from over charging and over discharging respectively both of which are destructive to the battery. The voltmeter monitored supply voltage to the fans while the ammeter monitored the current drawn by the fans. The voltmeter and ammeter readings were used to calculate the power consumed by the fans. The battery is shown in Figure 3.23

while auxiliary components are shown in Figure 3.24.

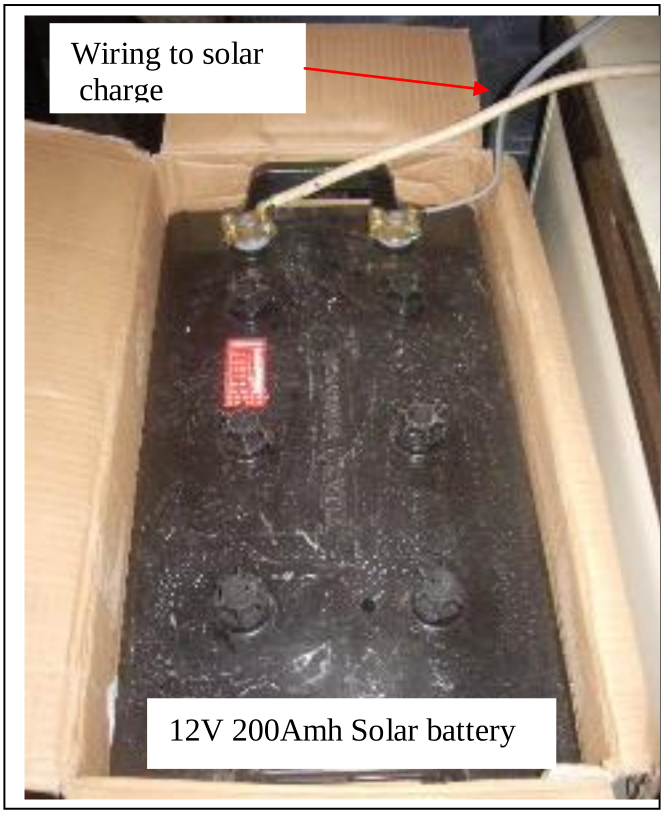


Figure 3.23 A 12V 200Ah solar battery

3.7 Experimentation design

Table 3.1 shows a summary of the tests conducted and their objectives. A total of eight preliminary and six final experiments were conducted. The preliminary experiments included one with unloaded dryer (No load test) as Test no. 1, and seven others with tomato loaded dryer (load tests). For the load tests, only one experiment was conducted using wet blankets (Test no. 2) to simulate the drying performance of high moisture content products while the rest six experiments were conducted with the dryer loaded with fresh sliced tomatoes. Three tests namely 6, 7 and 8 were redesigned to optimize energy in order to yield a quality dried product at minimum costs.

For comparison and repeatability of experiments, six final experiments were conducted with dryer loaded with 15kg of fresh tomatoes and the boiler powered from a 6kg LPG cylinder. For each run, the LPG burner was lit at 05.00hrs local time and allowed to heat the boiler water for two hours (up to 07.00hrs). The dryer was then loaded with sliced tomatoes and then fans were switched on at 07.00hrs marking the beginning of actual drying process and continued up to 18.30hrs. The LPG burner was left to burn until the LPG gas ran out. The final moisture content of the dried product at the end of each run was determined by the standard oven drying method by drying three samples of 50g of tomatoes at 60°C each until there was no change in weight. The moisture content was then calculated as described in Appendix C.

3.8 Calibration and measurements

Calibration was done by connecting copper-nickel chromium thermocouples type K via a data logger model Fluke 2286A made in USA and comparing their readings against time with those of mercury in glass thermometer at the ice point and during heating of the ice water to about 75^{o}C, a temperature range that was obtained in these experiments. The results were as shown in Table B-1 in Appendix B. By comparing thermocouple temperature readings against the values obtained simultaneously from mercury in glass thermometer, a linear calibration curve was obtained as shown in fig 3.24.

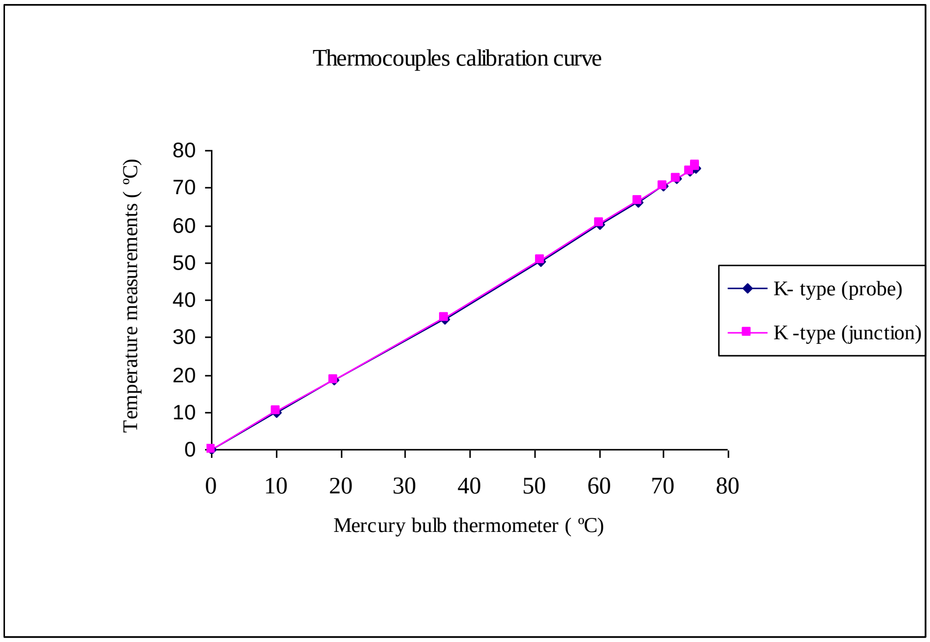


Figure 3.24 Thermocouple calibration curve

Table 3.1 A summary of tests and their objectives

Test No	**Type of test**	**Type of load in the dryer**	**Objective of the test**
1	No load test	Nil	To investigate the effect of airflow on the temperature profile within the unloaded drying chamber
2	On load test	Wet blanket materials	To test the ability of the dryer to dry high moist products.
3	On Load test	Sliced fresh tomatoes	To determine the moisture content of fresh tomatoes.
4	On Load test	Sliced fresh tomatoes	Thermal storage performance test with boiler water at 73°C.
5	On Load test	Sliced fresh tomatoes	(a) Boiler system temperatures (b) Thermal storage performance test with boiler water at 97.7°C.
6	On Load test	Sliced fresh tomatoes	To investigate an economical mode of operation that would minimize LPG consumption - LPG drawn from a 12kg cylinder
7	On Load test	Sliced fresh tomatoes	To investigate an economical mode of operation to that would minimize LPG consumption - LPG drawn from a 12kg LPG cylinder – (**This was a repeat of Test no.6)**
8	On Load test	Sliced fresh tomatoes	To confirm the economical mode of operation that would minimize LPG consumption as suggested in **Test no. 6** and repeated in **Test no. 7** (LPG drawn from a 6kg cylinder.
9-14	On Load test	Sliced fresh tomatoes	A repeat for **Test no. 8** for comparison and repeatability

3.8.1 Temperature measurements

The temperature data collection points are shown in Figure 3.35. Temperature measurements were monitored and recorded simultaneously at 15 minutes interval using calibrated copper-aluminium thermocouples type K (with a range of -200°C to +1200°C and a sensitivity of 41uV/°C) connected to data logger model Fluke 2286A with a sensitivity of 0.1°C. The data was then retrieved from the data logger and stored in a 1.44 MB ($3^{1}/_{2}$-inch) diskette inserted in the data logger. The monitored parameters at various positions are described as follows;

Position 1

This is the location where outer dry bulb temperature of the insulated wall of the boiler was measured using the arrangement shown in Figure. 3.25

Position 2

This is the location where the temperature of water entering the heat exchanger was measured.

Position 3

This is the location where the dry bulb temperature of the metal surface of the boiler was measured.

Position 4

This is the location where the dry bulb and wet bulb temperatures of the air entering the heat exchanger was measured. The temperatures obtained were also taken to be for the ambient air. The wet bulb temperature was measured using the arrangement shown in fig. 3.26

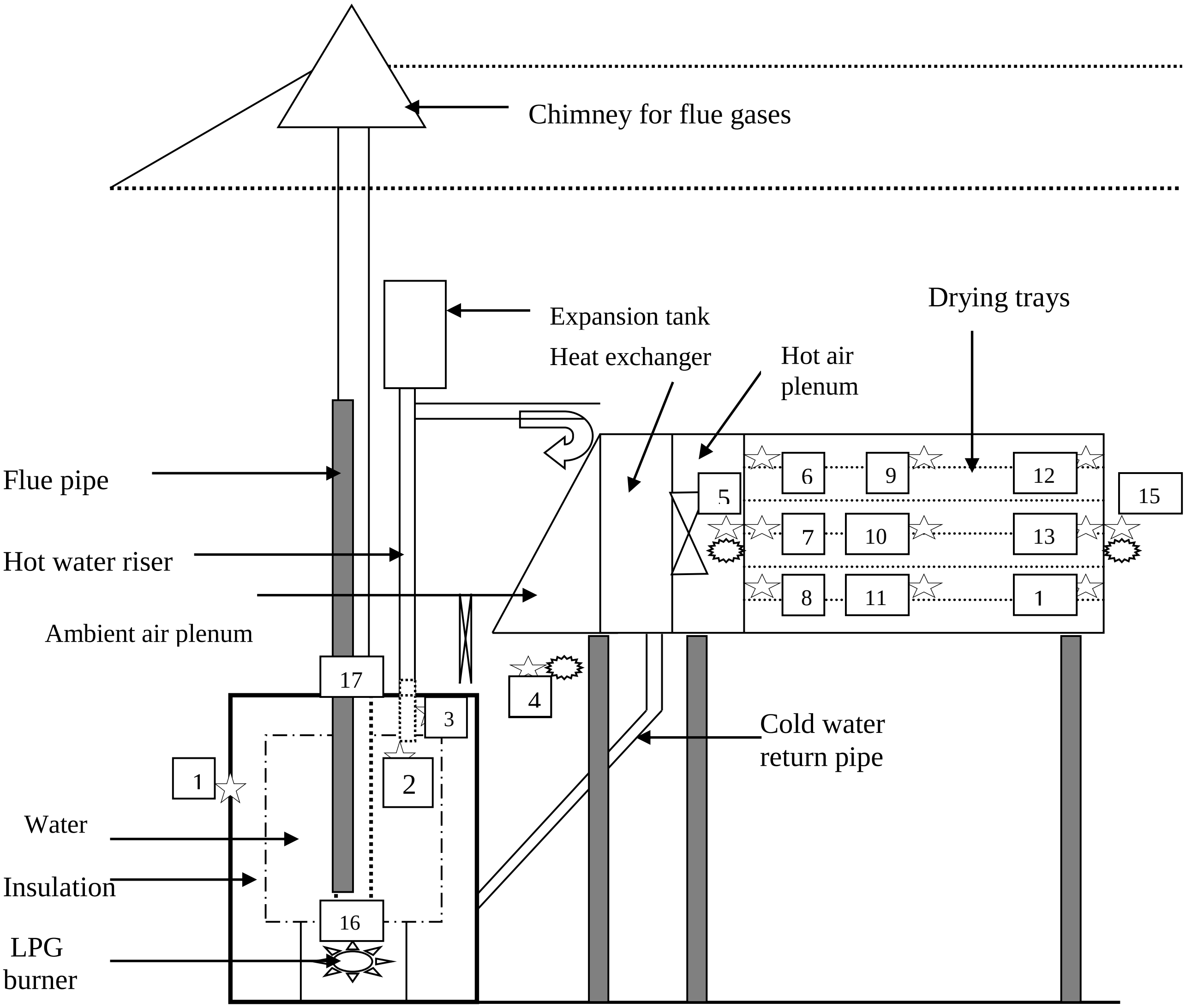


Figure 3.25 Experimental setup showing data measurement locations

Position 5

This is the location where the dry bulb and wet bulb temperatures of the air exiting the heat exchanger was measured. The wet bulb temperature was measured using the arrangement shown in Figure 3.26.

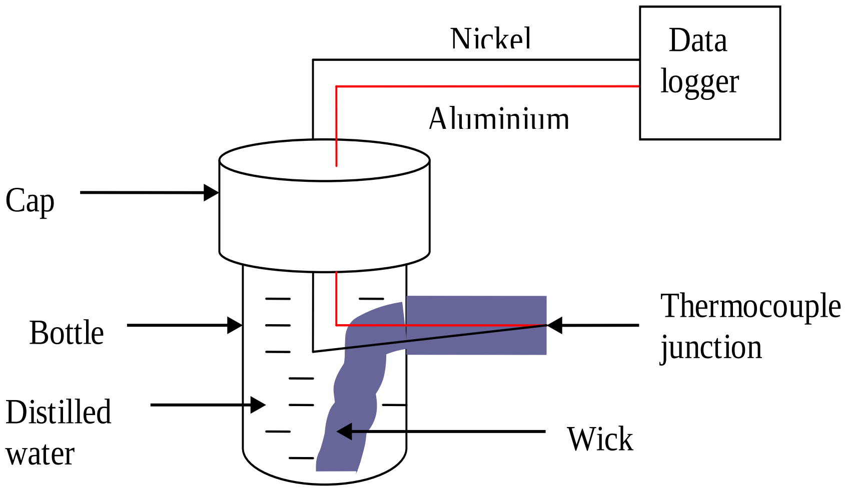


Figure 3.26 Wet bulb temperature measurement arrangement

Position 6, 7, 8

The dry bulb temperature measurements at the entry of the drying chamber were made using thermocouple arrangement shown in Figure 3.27 to give average temperature at different levels of the drying chamber.

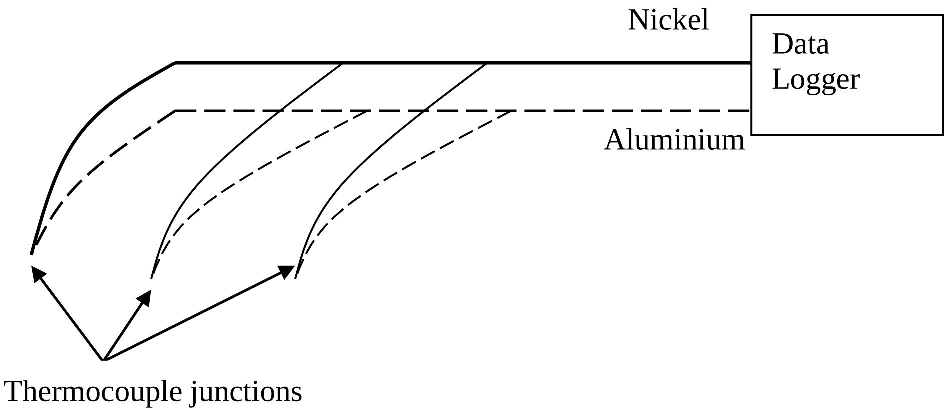


Figure 3.27 The average dry bulb sensor arrangement (Krishmaswamy, 2003)

Position 9, 10, 11

The dry bulb temperature measurements at the middle of the drying chamber along the height were made using thermocouple arrangement shown in Figure 3.27 to give average temperature at different levels of the drying chamber.

Position 12, 13, 14

The dry bulb temperature measurements at the exit end of the drying chamber were made using thermocouple arrangement shown in Figure 3.29 to give average temperature at different levels at the exit of the drying chamber.

Position 15

This is the location where the dry bulb and wet bulb temperatures just outside the exit side the drying chamber. The wet bulb temperature was measured using the arrangement shown in Figure 3.36.

Position 16 and 17

These were locations where the LPG burner flame temperature and flue exhaust gases temperature were measured respectively.

3.8.2 Relative humidity measurements

The relative humidity of ambient, dryer inlet and exit airs were obtained by subjecting respective wet bulb and dry bulb temperatures to psychometric relations.

3.8.3 Measurement of other variables

Other variables measured included solar radiation, airflow rate, LPG gas consumption, weight of fresh and dried tomatoes. Table 3.2 is a summary of these variables, instruments used to measure them, their accuracy as well as the method used.

Table 3.2 A summary of other variables measured during the experiments is shown below

Variable	**Instrument**	**Model**	**Accuracy**	**Method of measurement**
Solar radiation	Pyranometer	Kipp and Zenon (CN27-277)	91.68W/m^2 per mV	Connected to data logger model Fluke 2286A at 15 minutes interval placed on the roof top the workshop.
Airflow	Portable air velocity meter	VELOCICALC Model 8357	0.05m/s	Positioned at dryer exit. The airflow rate was obtained by multiplying the air velocity by cross-sectional area of the drying chamber.
LPG consumption	Calibrated spring-dial hoist scale with a maximum weighing capacity of 100kg	Not given	0.5%	The LPG cylinder was hoisted onto the spring balance. The weight indicated by the pointer was taken to be the weight in question.
Weight of fresh tomatoes	Calibrated electronic weighing balance with a maximum weighing capacity of 6.1kg	Denver instrument scale, MODEL XL-6100	0.1g	Fresh sliced tomatoes were placed in a container of known weight and placed onto the scale. Where the weight was above 6kg, they were weighed in batches. The total weight minus the weight of the container was the weight of fresh tomatoes per batch.
Weight of dried tomatoes	Calibrated electronic balance with a maximum weighing capacity of 2.2kg	Citizen CG2202, serial number 160191/06	100mg (0.01g)	Dried tomatoes were placed in polythene bags of known weight and placed onto the scale. The total weight minus the weight of the polythene bag was the weight of fresh tomatoes per batch.
Weight of dried tomatoes for moisture content determination	Calibrated electronic balance with a maximum weighing capacity of 2.2kg	Citizen CG2202, serial number 160191/06	100mg(0.01g)	Three crucibles plus their lids all of known weights were used. To each crucible, 50g of dried tomatoes were added and the final weights noted. The total weight (cooled crucible plus the tomatoes) minus the weight of the crucible plus the lid was the weight of oven dried sample.

3.9 Drying experiments

In order to determine and confirm the optimum operating point of the dryer, two categories of experiments namely preliminary and final experiments were conducted. Overall, only two sets (i.e Tests nos. 1 and 2) were conducted without tomatoes while the rest of the tests (Tests nos. 3-14 were done with the dryer loaded with sliced fresh tomatoes.

3.9.1 Preparation of tomatoes for drying tests

Fresh, firm, ripe and unblemished Roma tomatoes were purchased from the nearby Githurai open air market 25km East of Nairobi. They were washed and dried with a clean cloth and then sliced into 6mm circular pieces. Using an electronic weighing balance type Denver instrument scale, MODEL XL-6100 with accuracy of ±0.1g, the weight of the sliced tomatoes was determined. The slices were then spread in the drying tray in a single layer with a spacing distance of 1cm to 2 cm. Drying them in small sized slices was aimed at reducing drying time and maintaining high quality of the dried tomato (Giovanelli *et al.*, 2002). Figure 3.28 shows typical tomato samples used in the drying trials while Figure 3.29 shows sliced tomato spread uniformly in the trays awaiting loading into the drying chamber. Figure 3.30 shows loading of the drying trays in the drying chamber. For comparison with sun drying, samples were dried simultaneously with the LPG dryer sample.

Figure 3.28 Tomato samples used in the trials

Figure 3.29 Trays loaded with uniformly sprad sliced tomatoes

Figure 3.30 Loading of drying trays into the drying chamber.

3.9.2 Preliminary experiments

The general objective of the preliminary experiments was to establish the optimum operating point of the LPG dryer. To achieve this, eight experiments were conducted each with a specific objective as shown on Table 3.2. Each test began by preheating the boiler water for a given duration with the fans OFF. Once the preheating process was completed, the fans were switched ON and monitoring of various data done. Whether the burner remained ON or OFF was dependent on the specific objective of that particular test. During tests nos. 1-5, the fans were powered from an AC/DC bench power supply model RADFORD LABPACK type LAB59 with a voltage output range of 0-20 Volts switchable in 2V increments. Test no.1 was also repeated with fans powered from a 2 by 50W/200Ah PV/battery system, and the drying bin temperatures determined under similar experimental conditions. The last three preliminary experiments namely, 6, 7 and 8, were redesigned by placing the AC/DC power supply with 2 by 50W/200Ah PV/battery system, increasing the airflow rate to $0.43m^3/s$ from $0.23m^3/s$ and by reducing the preheating period to 2 hours. The use of PV/battery system would also be a simulation of rural areas not connected to the grid.

3.9.3 Determination of initial moisture content of fresh tomatoes

The initial moisture content of tomatoes was determined in test no.3. The boiler water was preheated from 21.9^{o}C to 92.1^{o}C from 07.00hr to 11.30hr (about 4.5 hours) with both fans OFF and under no load condition. After the preheating period, the dryer was loaded with 9.5kg of fresh tomatoes and both fans switched ON providing an airflow of 0.28m3/s. Six random samples of tomatoes were placed in at the centre of the top, middle and bottom trays in each of the left and right compartments of drying chamber and dried concurrently with the 9.5kg of tomatoes. During the drying process, the burner remained ON for additional 7.5 hours so as to maintain a high water temperature. Keeping the water temperature above 80^{o}C was necessary in order to achieve a temperature range of 50-57oC in the drying bin which is recommended for drying fruits and vegetables (Zanoni ***et al.,*** 1998: Shi ***et al.,*** 1999) A seventh sample was dried concurrently in the sun.

After 7.5 hours of drying, the burner was switched OFF but the drying process

Table 3.3 Preliminary experiments

Test No and Date	**Type and weight of load in the dryer**	**Objective of the test**	**Initial boiler water temp (ºC)**	**Preheating period**	**Boiler water temp after preheating (ºC)**	**Avearge drying bin temperature**	**Airflow (m^3/s)**	**LPG burner condition during drying period**
1	Nil	Effect of airflow on the temperature profile within the unloaded drying chamber	23.3	4.5	97		0.19,0.23, and 0.28, 0.43	ON until a set of nine runs were completed (i.e 3 runs for each airflow setting)
2 10-09-2008	13.5kg of wet blanket Materials	Ability of the dryer to dry high moist products.	36.4	3	80.4	41.9	0.28	ON for 2 hours
3 18-09-2008	9.5kg of sliced fresh tomatoes	Moisture content of fresh tomatoes.	21.9	4.5	92.1	50.5	0.28	ON for 7.5 hours
4 25-10-2008	9kg of sliced fresh tomatoes	Thermal storage performance test with boiler water at 73ºC.	21.2	3.5	73.3	35.5	0.28	OFF
5 06-11-2008	6.9kg of sliced fresh tomatoes	(a)Thermal storage performance test with boiler water at 97.7ºC. (b) Boiler system temperatures	22.9	4	97.7	42.9	0.28	OFF
6 29-11-2008	6.9kg of sliced fresh tomatoes	Optimum mode of operation that would minimize LPG consumption - LPG drawn from a 12kg cylinder	23.6	2	62.5	43.5	0.43	ON for 7.5 hours
7 04-12-2008	15.5kg of sliced fresh tomatoes	A repeat of Test 6 (- LPG drawn from a 12kg cylinder)	23.6	2	61.8	42.0	0.43	ON for 7.5 hours
8 04-03-2009	16.9kg of sliced fresh tomatoes	A repeat of Tests 6 and 7 (LPG drawn from a 6kg cylinder.	23.3	2	65.6	40.2	04.3	ON for 7.5 hours

continued supported by the energy from the thermal storage. The drying process was terminated when the dried tomatoes were leathery and pliable. All the samples were weighed on an hourly interval and their weights recorded as shown on Table B-4 of Appendix B. Solar drying was discontinued after the seventh hour (i.e 18.36 hr local time). The process resumed on the second day from 08.46hr to 18.46hr local time with a final weight of of 14.3g. On the third day, the process was terminated at 15.00hr with a final weight of 11.2g. The final weight (W^d) of the samples was determined by the standard dry oven method. The initial moisture content (wet basis) was calculated using equation (3.1) and the results shown on Table B-5 of Appendix B.

$$Mw_t = \frac{W_t - W_d}{Wt} \times 100(\%) \qquad (3.1)$$

The moisture content at each weighing interval was calculated usng equation (3.2) and the results shown on Table B-6 of Appendix B.

$$Mw_i = \frac{W_i - W_d}{W_i} \times 100(\%) \qquad (3.2)$$

To determine the drying rate, grams of water/ grams of dry solids at each weighing interval was calculated using equation (3.3) and the drying rate was determined using equation (3.4) (Itodo et al. 2002; Bolaji and Olalusi, 2008).

$$Mw_i = \frac{W_t - W_d}{W_d} \qquad (3.3)$$

$$\frac{dm}{dt} = \frac{Mi - Mf}{t} \times 100\% \qquad (3.4)$$

The average weight, moisture content (wb) and drying rate data for the LPG dried sample as compared to that of the sun drying are shown on Table 4.3.

3.9.4 Final experiments; Tests 9-14

For comparison and repeatability of experiments, six final experiments were conducted with dryer loaded with 15kg of fresh tomatoes and the boiler powered from a 6kg LPG. For each run, the LPG burner was lit at 05.00hrs local time and allowed to heat the boiler water for two hours (up to 07.00hrs) with the fans OFF. At 07.00hrs the dryer was loaded with 15kg tomatoes and the fans switched ON providing an airflow of $0.43m^3/s$. The LPG burner remained ON until the gas was fully consumed. The drying process was terminated at 18.30hrs. The LPG gas lasted for a total of 9.5 hours (2 hours during preheating and 7.5 hours during drying). Summarized conditions during preheating of boiler water and tomato drying process are shown on Tables 3.4 and 3.5 respectively. The raw data obtained is shown in Appendix F. The moisture content of gthe dried product at the end of each run was determined by the standard oven drying method. The initial moisture content of the original sample used for each run was then calculated using the equation;

$M_{wt} = M_C \ [(W^1 - W_F)/(100 - W_F)]$ (Excell,1980).

Table 3.4 Summary of boiler preheating tests.

Test No.	**9**	**10**	**11**	**12**	**13**	**14**
Date	09-05-2009	15-05-2009	21-05-2009	25-05-2009	30-05-2009	04-06-2009
Burner condition	ON	ON	ON	ON	ON	ON
Start time (local time)	05.00am	05.00am	05.00am	05.00am	05.00am	05.00am
Stoppage time (local time)	07.00am	07.00am	07.00am	07.00am	07.00am	07.00am
Preheating duration (hours)	2	2	2	2	2	2
Initial boiler water temperature (ºC)	23.2	22.7	24.5	24.1	22.8	24.4
Final boiler water temperature (ºC)	63.2	60.6	64.5	64.1	61.8	59.2
Fan condition	OFF	OFF	OFF	OFF	OFF	OFF
Drying bin condition	Empty	Empty	Empty	Empty	Empty	Empty
Ambient temperature ((ºC)	21.9	21.8	22.6	22.3	21.3	22.6
Ambient relative humidity (%)	77.6	83.1	78.8	77.7	83.0	75.7
Initial weight of LPG cylinder plus gas (kg)	15	15	15	15	15	15
Final Weight of LPG cylinder plus gas (kg)	12.5	12.5	12.5	12.5	12.5	12.5

Table 3.5 Summary of preliminary drying tests.

Test No.	**9**	**10**	**11**	**12**	**13**	**14**
Date	09-05-2009	15-05-2009	21-05-2009	25-05-2009	30-05-2009	04-06-2009
Start time (local time)	07.00am	07.00am	07.00am	07.00am	07.00am	07.00am
Stoppage time (local time)	18.30pm	18.30pm	18.30pm	18.30pm	18.30pm	18.30pm
Drying duration (hours)	11.5	11.5	11.5	11.5	11.5	11.5
Fan condition	ON	ON	ON	ON	ON	ON
Airflow (m^3/s)	0.43	0.43	0.43	0.43	0.43	0.43
Burner condition	ON for 7.5hrs	ON for 7.5hrs	ON for 7.5hrs	ON for 7.5hrs	ON for 7.5hrs	ON for 7.5hrs
Initial boiler water temperature (ºC)	63.2	60.6	64.5	64.1	61.8	59.2
Final boiler water temperature (ºC)	38.3	37.9	39.3	41.1	40.3	46.0
Initial ambient temperature ((ºC)	20.8	21.0	21.7	20.5	20.5	21.4
Initial ambient relative humidity (%)	81.9	77.9	80.7	81.8	86.0	78.2
Final ambient temperature ((ºC)	24.5	23.4	22.9	22.5	23.2	25.2
Final ambient relative humidity (%)	61.9	67.5	69.1	74.1	64.3	61.1
Initial load of tomatoes in the dryer (kg)	15	15	15	15	15	15
Final weight of dried tomatoes (kg)	0.87	0.88	0.93	0.94	0.98	1.06
Initial moisture content (%) (wb)	94.8	94.7	94.5	94.5	94.0	93.5
Final moisture content (%) (wb)	10.3	9.7	11.3	12.2	9.3	8.0

3.10 Economic analysis of the LPG dryer

3.10.1 Introduction

Economic analysis was carried out based on capital cost for the construction of the LPG dryer as shown on Table D-1. The economic parameters were based on the economic situation in Kenya as well as the daily output of the LPG dryer as shown on Table D-2. The retail price of 200g of sun dried tomatoes at Ms Chandarana Supermarket situated at Muthaiga Shopping Complex, 5km South of Nairobi was Ksh 385 ($4.80).

3.10.2 Methods of economic analysis.

In this study, the annualized cost method (Kalbande and Jadhev (2007); Sreekumar ***et al.,*** 2008) as well as Life Cycle saving and payback period methods (Singh ***et al.,*** 2006; Sreekumar ***et al.,*** 2008) were used to carry out the economic analysis of the LPG dryer. In carrying out the economic analysis, it was assumed that the LPG drier-dried product would cost the same as that of sun-dried tomatoes available in the market. Thus the selling price of 1kg of tomatoes was Ksh 1925 ($24). In the annualized cost method, the annualized cost of the dryer was calculated and the cost was divided by the amount of the product dried per year to obtain the cost of drying per unit weight of the dried product.

In the Life Cycle Savings method, the first step was to determine the total annual savings per year for the LPG dryer in the base year. Then, the present worth and the cumulative present worth of the annual savings over the life of the systems were calculated. The internal rate of return (IRR) was also calculated. The Payback period equation (3.5) was applied to the life cycle savings to determine the payback period. Calculations for the economic analysis are shown in Appendix D while the analysis is summarized on Tables 4.10.

$$n_p = \frac{\ln\left[1 - \frac{C}{S_1}(r - i)\right]}{\ln\left(\frac{1+i}{1+r}\right)} \qquad (3.5)$$

3.11 Efficiency of the LPG dryer for tomatoes

Several efficiencies were calculated based on;

Heat input and output in the drying air

Energy stored in the boiler water and latent heat of vaporisation

Energy stored in the boiler water and the minimum heat (sensible plus latent) supplied to the tomatoes.

Total energy contained in 6.6kg of LPG (assuming the efficiency of the LPG burner was 100%) and latent heat of vaporization only.

Total energy contained in 6.6kg of LPG (assuming the efficiency of the burner was 100%) and the minimum heat (sensible plus latent) supplied to the tomatoes.

Detailed calculations of efficiency are shown in Appendix E.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

This section consists of results obtained from preliminary and final drying performance tests, economic analysis as well as thermal efficiency of the LPG dryer. It also contains of discussions on how the results compare with earlier work by other researchers. The final product is shown in Figure 4.1. A summary of results obtained during the preliminary and final drying performance tests is shown on Tables 4.1 and 4.2 respectively.

Figure 4.1 Dried tomato product

4.2 Effect of airflow rate on temperature profile

Since the drying chamber consisted of two compartments each with a set of five trays stacked one over the other, it was necessary that the temperature profile be investigated both across the height and the length of the drying chamber. Tables 4.1 shows a summary of preliminary tests performed in order to determine the best mode of operating the dryer. Table 4.2 shows the summarized results of drying performance during the final tests. Figure 4.2 shows the temperature profile across the height of the dryer with an airflow of $0.43m^3/s$. Trays nos. 1, 3 and 5 whose temperatures were monitored were at 6, 20 and 34cm from the bottom of the drying bin. Figure 4.3 shows the temperature profile across the 2m length drying chamber for an airflow of $0.43m^3/s$. For each of the airflow, the temperature variations for all the positions monitored were less than 1.5^oC. Thus the drying bin temperature was considered uniform both along the height and the length of the drying chamber and therefore the rotation of drying trays during drying was not recommended.

Also from Tables 4.1 and 4.2, it was observed that for all the positions monitored, an increase in the airflow into the drying chamber resulted to lower temperatures. A high airflow means a large mass flow rate of air passing through the heat exchanger. If an equal amount of heat energy is applied to two substances of the same specific heat capacity and the same initial temperature but different masses, the smaller mass would have a higher final temperature than the larger one.

Table 4.1 Summarized results of the drying performance during preliminary tests

Test No.	**3**	**4**	**5**	**6**	**8**	**8**
Date	18-09-08	25-10-08	06-11-08	27-11-08	04-12-08	04-03-08
Fan condition	ON	ON	ON	ON	ON	ON
Burner condition	ON(7.5hrs)	OFF	OFF	ON(7.5hrs)	ON(7.5hrs)	ON(7.5hrs)
Airflow (m^3/s)	0.23	0.43	0.43	0.43	0.43	0.43
Average boiler water temperature ((^{o}C)	83.6	54.1	62.0	70.5	68.8	66.3
Final boiler water temperature (at end of drying) (^{o}C)	56.8	40.1	40.6	52.5	47.9	36.3
Average boiler outer temperature (^{o}C)	30.5	32.1	28.9	27.8	29.1	26.3
Average ambient temperature (^{o}C)	25.1	26.1	24.4	24.0	23.5	24.3
Average ambient relative humidity (%)	61.6	63.6	70.4	64.6	72.0	57.6
Average drying bin temperature (^{o}C)	50.5	45.5	42.9	43.5	42.0	40.2
Initial load of tomatoes in the dryer (kg)	9.5	10	6.9	6.9	15.5	16.9
Final weight of dried product (kg)	0.7	4.2	2.1	0.5	1.1	1.1
Mass of water removed (kg)	8.8	5.8	4.8	6.4	14.4	15.8
Initial moisture content (%) (wb)	93.7	93.7	93.7	93.7	93.7	93.7
Initial moisture content (%) (wb)	15.0	85.0	79.0	17.0	17.5	13.0
Initial weight of LPG gas cylinder (kg)	22.5	25	22.5	25.5	19	15
Final weight of LPG gas cylinder (kg)	12.5	22.5	19.5	19	12.5	8.5
Mass of LPG consumed (kg)	10	2.5	3	6.5	6.5	6.5
Drying period (hrs)	10.3	3.5	4.7	10.0	10.0	11.5
Average solar radiation (W/m^2)	-		-	-	-	402.1

Table 4.2 Summarized results of the drying performance of the LPG dryer during optimization tests.

Test No.	**9**	**10**	**11**	**12**	**13**	**14**
Date	09-05-2009	15-05-2009	21-05-2009	25-05-2009	30-05-2009	04-06-2009
Start time (local time)	07.00am	07.00am	07.00am	07.00am	07.00am	07.00am
Stoppage time (local time)	18.30pm	18.30pm	18.30pm	18.30pm	18.30pm	18.30pm
Fan condition	ON (7.5hrs)	ON (7.5hrs)	ON (7.5hrs)	ON (7.5hrs)	ON (7.5hrs)	ON (7.5hrs)
Airflow (m^3/s)	0.43	0.43	0.43	0.43	0.43	0.43
Highest boiler water temperature ((°C)	86.5	80.4	81.3	83.9	81.9	85.4
Final boiler water temperature (°C)	38.3	37.9	39.3	41.1	40.3	46.0
Average boiler water temperature ((°C)	68.0	66.2	68.2	69.5	67.5	70.7
Average boiler outer temperature (°C)	26.0	24.7	28.3	28.1	26.6	29.9
Average ambient temperature (°C)	24.4	24.1	22.9	23.0	23.5	25.5
Average ambient relative humidity (%)	65.0	67.5	72.0	70.6	68.2	59.3
Average drying bin temperature (°C)	40.8	40.1	40.7	41.6	40.6	43.3
Initial load of tomatoes in the dryer (kg)	15	15	15	15	15	15
Final weight of dried product (kg)	0.87	0.88	0.93	0.94	0.98	1.06
Mass of water removed (kg)	14.13	14.12	14.07	14.06	14.02	13.94
Initial moisture content (%) (wb)	94.8	94.7	94.5	94.5	94.0	93.5
Initial moisture content (%) (wb)	10.3	9.7	11.3	12.2	9.3	8.0
Drying period (hrs)	11.5	11.5	11.5	11.5	11.5	11.5
Total LPG consumed	6	6	6	6	6	6
Average solar radiation (W/m^2)	491.3	363.3	240.6	275.6	434.3	469.6

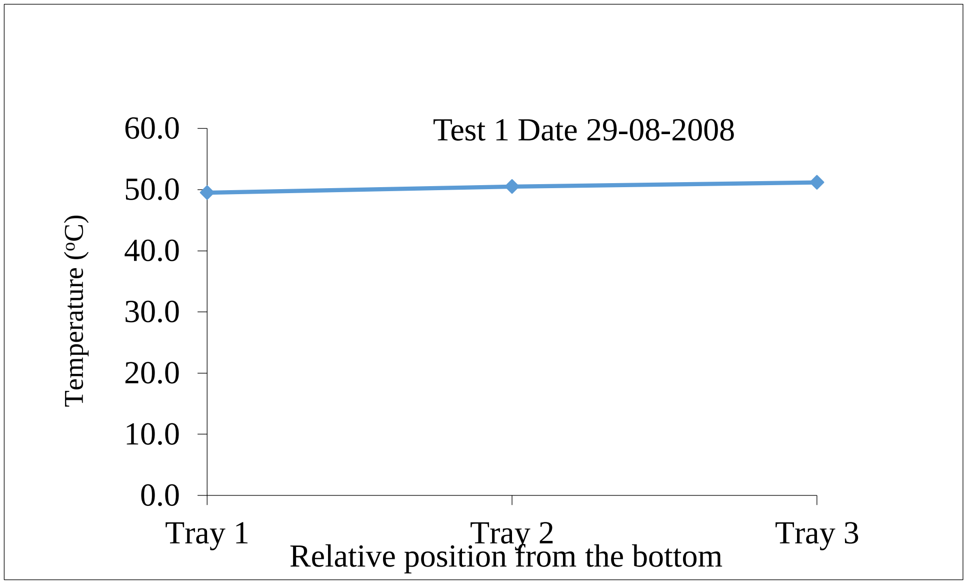


Fig 4.2 Temperature profile across the height of the dryer at anairflow of 0.43m^3/s

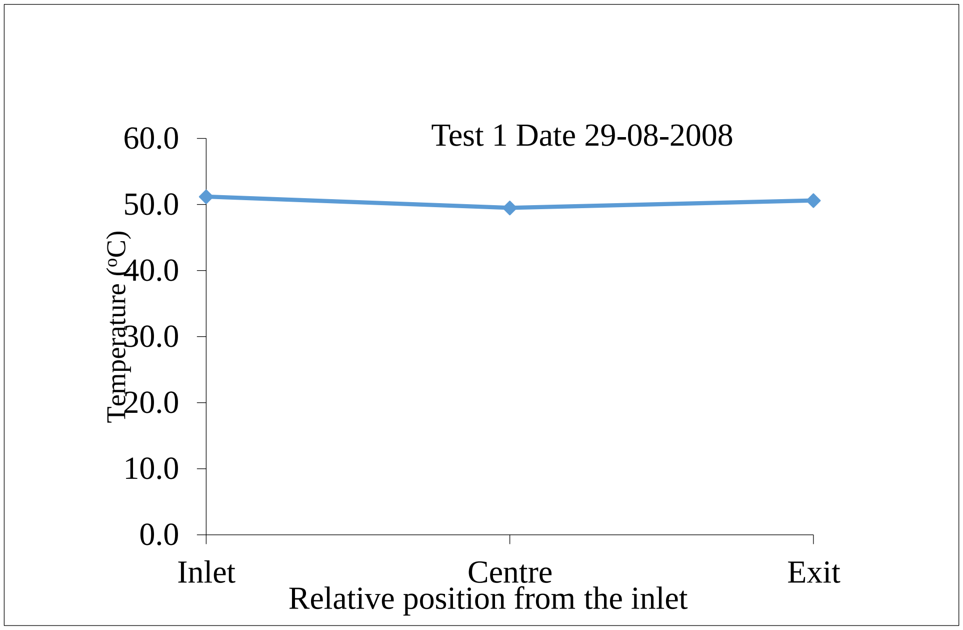


Fig 4.3 Temperature profile across the length of the dryer at an airflow of 0.43m^3/s

Satter (2003) reported similar temperature variations along the height and length of the drying chamber of a portable copra dryer. In his experiments the airflow was defined by the percentage of the air vent opening. At three different openings namely; 100, 50 and 5%, temperatures were monitored on 5 different positions along the length of the three wire mesh trays stacked one over the other at 5, 20 and 60cm from the top. The average temperatures observed on all the trays positions at 100, 50 and 5% opening of the air vent were 40, 55 and 80^{o}C respectively.

4.3 Performance of the LPG dryer and its comparison with sun drying

A summary of the performance of the LPG dryer as compared to that to that of the sun drying is shown in Table 4.3 and Figures 4.4 and 4.5.

Table 4.3 Comparison of moisture removal and drying rate for LPG and Sun and dried samples.

Time (Hrs)	**Dryer-dried load**			**Sun-dried load**		
	Average weight of LPG dryer sample	**Moisture (%) (wb)**	**(g water/g dry.hr)**	**Weight (g)**	**Moisture (%) (wb)**	**(g water/g dry.hr)**
0	220.0	93.6	14.7	198.1	94.7	17.9
1	179.2	92.2	11.8	17.13	93.9	15.3
2	144.3	90.3	9.3	144.2	92.7	12.7
3	109.4	87.2	6.8	122.7	91.4	10.7
4	78.4	82.1	4.6	102.6	89.8	8.8
5	55.4	74.7	3.0	86.8	87.9	7.3
6	39.3	64.4	1.8	73.5	85.7	6.0
7	29.7	52.9	1.1	65.5	84.0	5.2
8	24.3	42.3	0.7	65.5	84.0	5.2
9	21.4	34.5	0.5	65.5	84.0	5.2
10	17.7	20.8	0.3	65.5	84.0	5.2

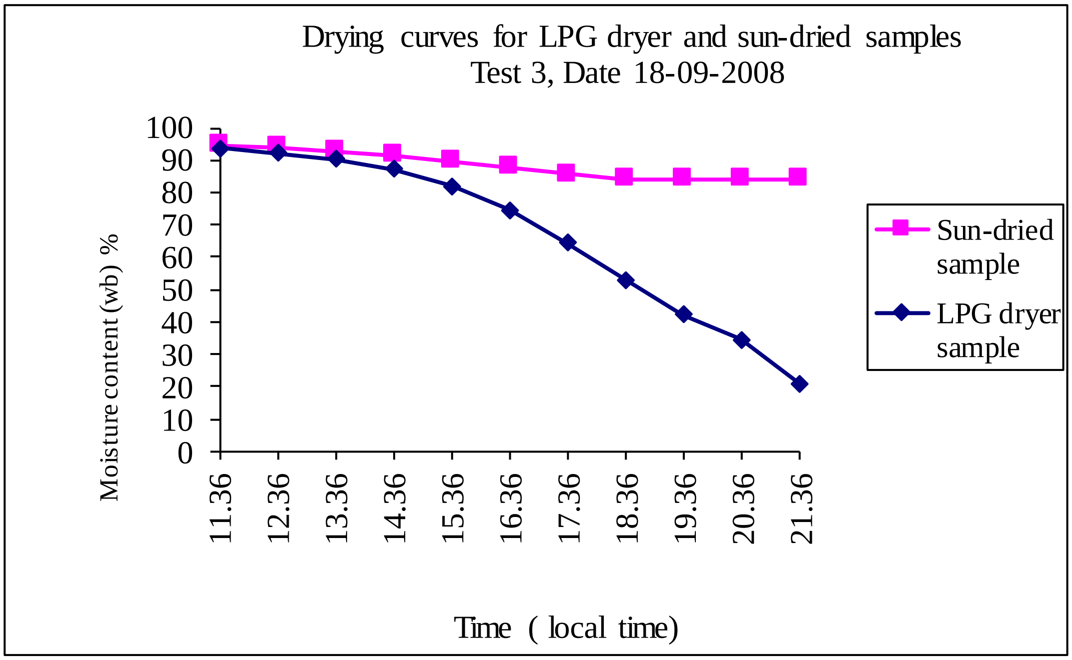


Figure 4.4 Moisture content (wb) versus drying time for LPG dryer and sun dried tomatoes

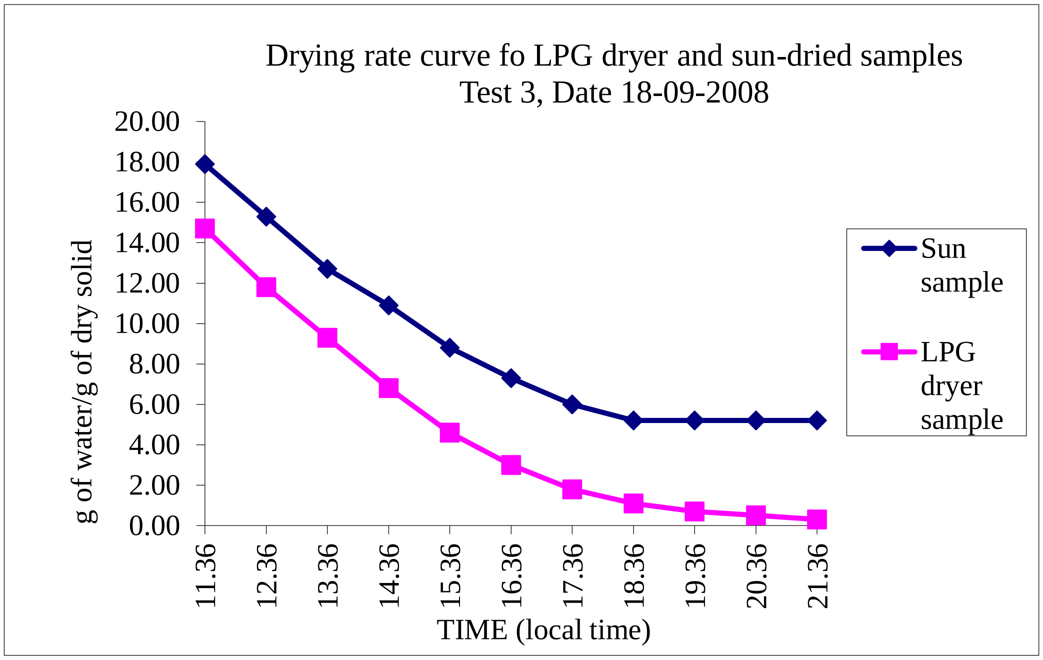


Figure 4.5 Comparison of the dry basis moisture versus drying time for LPG and sun dried samples.

Drying was very fast in the initial hours of operation, and then gradually decreased. This was because of the evaporation of the surface moisture at the beginning of the process. Moisture removal was higher in the LPG dryer than in sun drying method. Both the moisture removal and drying rate curves were exponential in nature though they had a different starting point occasioned by the slightly different calculated initial moisture content for the LPG dryer and sun dried samples. However, after the 7th hour, both curves for the sun-dried sample are flat because the there was no more sunlight and the sample was moved indoors while the LPG dryer continued to dry.

Exponential drying curves have been reported by Krodika *et al.* (2003) and Bon *et al.* (1997). For the LPG sample, the drying rate initially increased rapidly at 2.9 g of water/g of dry solids/hour for the first one hour and then entered a constant rate period of 2.5g of water/g of dry solids/hour for 2 hours. For the sun dried sample, the first 2 hours had a constant drying rate of 2.6g of water/g of dry solids/hour. In this study, with an airflow of 0.9m/s (0.28m^3/s) and at a temperature of 50.5^{o}C, the average drying rate for tomatoes in the LPG dryer for the first 2 hours was 2.7g of water/g of dry soilds/hour. Robertson and Lupien (2008) reported the drying rates of Roma tomatoes for first 2.5 hours as shown on Table 4.4.

Table 4.4 Initial water removal rates for various drying conditions of Roma tomatoes

Drying conditions (Air velocity (m/s)/drying temperature (°C))	**Water removal rate (drying rate) (g of water/g of dry solids/hour)**
0.1/50	1.73
0.1/58	2.01
0.5/50	2.71

Source: Robertson and Lupien (2008)

Thereafter, the drying rates decreased as the drying process entered the subsequent falling rate. The short constant rate period signified the non-porosity nature of the tomatoes since in non-porous solids, only the superficial moisture is removed during constant rate period (Lidhoo, 2005).

4.4 Initial moisture content of fresh tomatoes

The initial moisture content for fresh tomatoes ranged from 93.1-94.7% with an avaerag of 93.7% as shown on Table B-5 of Appendix B. Other researchers have reported the moisture content of fresh tomatoes as between 90-92% (Andristos *et al.*, 2003; 94% (Barb, 1985) and bwtween 93-95% (Robertson and Lupien, 2008).

4.5 Drying time and final moisture content of dried tomatoes

A critical moisture content of less than or equal to 15% should be attained so as to safely store dried tomatoes (Zanoni *et al.*, 1998; Brooks *et al.*, 2008). From preliminary test number 3 in Table 4.1, it took 10.3 hours to achieve a final moisture content of 15% at airflow and average drying temperature of 0.28m^3/s and 50.5°C respectively.

Further tests showed that with an increased airflow the critical moisture content could be obtained while operating at lower temperatures but with a longer drying duration. In particular test number 14 in Table 4.2 , with an airflow and average dryer temperature of 0.43m^3/s and 43.3°C a final moisture content of 8% was obtained within 11.5 hours of drying. Open-air drying took 3 days with 26 hours of effective drying to achieve a critical moisture content of 15% and below.

Lidhoo (2008) reported that it requires 9 and 3 hours to dry sliced tomatoes at 45°C and 95°C respectively to the critical moisture content of 15% (wb). Brooks *et al*. (2008) reported 36, 26 and 20 hours and 23, 18 and 13 hours as the time required to dry tomato halves, quarters and eighths at 55°C and 65°C respectively to attain a critical moisture content of 15%. Drying times of 2 to 10 hours at drying temperatures of 60 to 110°C and air flow rates of 0.5 to 2.0 m/s (using cross-flow arrangements) have been reported by several authors (Olorunda *et al*., 1990; Hawlader *et al*., 1991; Zanoni *et al*., 1998; Krokida *et al*., 2003).

4.6 Effect of boiler water temperature on drying bin temperature

It was observed that the drying bin temperature was dependent on boiler water temperature. From Test no.3 it was observed that average boiler water temperature of 83.6^{o}C resulted to average drying bin temperature of 50.5^{o}C. Similarly, from the final test (9-14), an average boiler water temeperature of between 66-70^{o}C resulted to drying bin temperatures in the range between 40-43^{o}C. The results compares well with those obtained by Hirunlabh *et al.* (2004) on the study of chilli and garlic drying using waste heat recovery from geothermal energy. With the geothermal waste water at 80^{o}C, they reported average drying temperatures of between 34.8-40.6^{o}C and 44.9-50.4^{o}C during garlic and chilli drying respectively. Andristos *et al*. (2003) also reported a dryer inlet air temperature of 55^{o}C when ambient air with a temperature range of between 20-35^{o}C was heated with geothermal waste at a temperature of 59^{o}C.

4.7 Thermal storage drying test

An attempt was made find out how far the drying process could last with the LPG burner before the drying temperatures could fall below 32^{o}C. The water was heated to different temeperatures of 73.3^{o}C and 97^{o}C thereby 2.5kg and 3.0kg of gas respectively. The drying process lasted longer with the boiler water at 97.0^{o}C than at 73.3^{o}C before the average dryer temperature dropped to 30^{o}C with a final moisture content of 79% (wb) and 85% (wb) respectively. Table 4.5 gives a summary of this test which showed that energy from the thermal storage alone was not enough to completely dry the tomatoes to the required critical moisture of 15% (wb) dry basis.

Table 4.5 Drying performance of the thermal storage

Boiler water temperature (^oC)	LPG consumed (kg)	Duration of drying supported by the thermal storage (hrs)	Final moisture content (%)
73.3	2.5	4.0	85
97.0	3.0	4.75	79

4.8 Variation of boiler system temeperatures during preheating

The data obtained for test 5 during preheating of the boiler water is shown on Table B-7 of Appendix B while a graphical presentation of the same is shown in Figure 4.6. It was observed that the boiler water and boiler metal clad temperatures rose alsmost linearly at an average rate of 17.2^{o}C/hr and 12.2^{o}C/hr respectively. The ambient temperature was fairly constant at about 20^{o}C. The boiler outer surface and the ambient tempeartures were failry close to one another with a highest difference of 8.9^{o}C. Hence the insulation was reasonably effective. The average temperatures obtained from the combustion of LPG gas was 1228^{o}C while the exhaust flue gas was at 191.4^{o}C. The LPG combustion temperature compared well with that of natural gas (1215oC as reported by Bergles *et al.* (1991).

4.9 Optimum operation mode of LPG dryer

From the raw data of tests numbers 9 to 14 on Tables F-9 to F-14, it was observed that by first heating the boiler water for two hours with the fans OFF a boiler water temperature of between 59.9^{o}C to 64.5^{o}C was achieved. The average drying chamber temperatures were between 31.2^{o}C to 33.1^{o}C. This made it possible to start the the drying process at these temperatures and mostly rely on the high airflow of 0.43m^{3}/s while continuing the heating process. The mode of operation remarkably reduced the consumption of LPG from 10kg to 6.6kg. Studies reported on LPG powered dryers did not have thermal storage systems.

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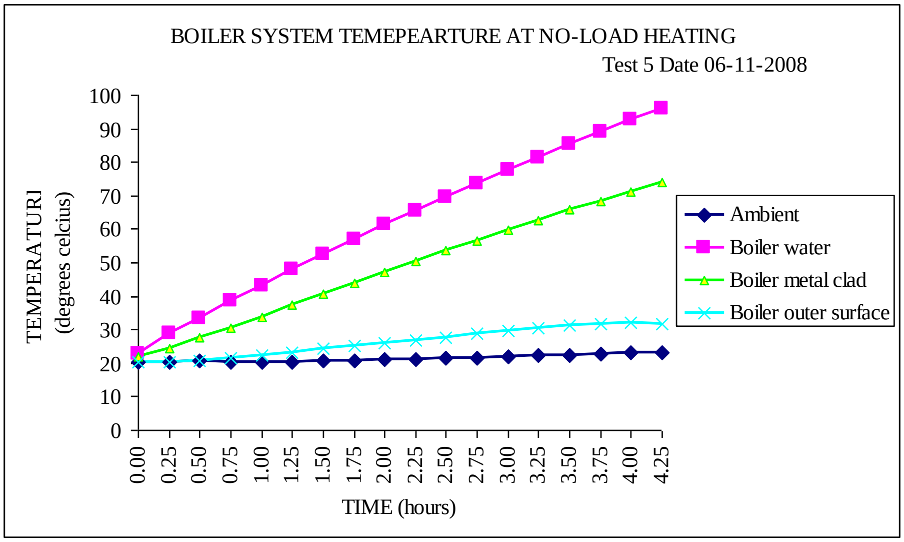

Figure 4.6 Typical boiler system temperatures profiles during preheating of the boiler water

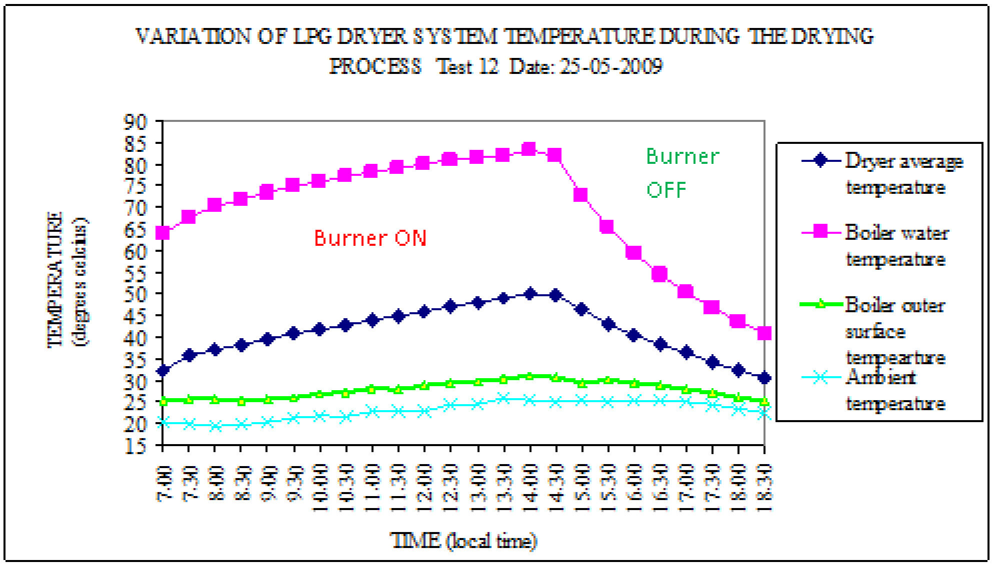

Figure 4.7 Variation of LPG dryer temperatures during drying test no.12

In such systems, the drying air was heated indirectly by combustion gases from the LPG burner through a heat exchanger. The systems were basically for complementary solar drying. Figures 4.7 shows the variation of various LPG dryer temperatures during the drying process for a selected run. As long as the burner was ON the boiler water and dryer average temperatures rose almost linearly to their maximum high temperatures of about 85^{o}C and 52^{o}C respectively before starting to decline after LPG gas ran out. The energy stored in the boiler was able to support the drying process for four hours after the burner was OFF before the average drying chamber temperature dropped to about 30^{o}C.

4.10 Solar radiation and ambient temperature for a clear sky condition at Kenyatta University, Nairobi, Kenya

Figure 4.8 shows a variation of ambient temperature and solar radiation for a typical drying day. The solar radiation increased with time from 22.9W/m^2 at 07.00hr to a maximum of 842.5Wm^2 at 12.30pm. Between 11.00hr and 15.00hr, the solar radiation was almost constant. Thereafter, the solar radiation enetered a falling region and dropped to 0.9W/m^2 at 18.30hr. This could be explained by the fact that during this period, the sun's rays were almost perpendicular to the solar radiation measuring equipment, making it to receive a high and almost constant solar radiation. The ambient temperature increased progressively from 21.4^{o}C at 07.00hr to a maximum of 28.4^{o}C at 15.30hr within the day due to conscious accumulation of heat on the earth's surface caused by trapped sun rays by the air molecules. The ambient air temperature then entered into an almost constant region between 15.30hr to 17.30hr before dropping to 25^{o}C at 18.30hr. The average solar radiation and ambient temperature for the day were 469.6W/m^2 and 25.5^{o}C respectively.

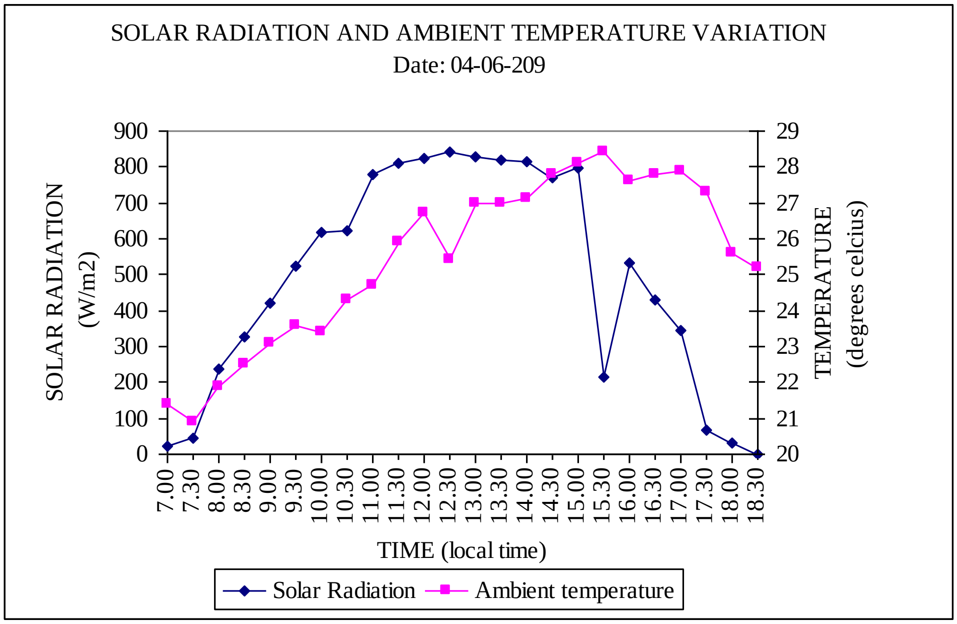

Figure 4.8 Average solar radiation and ambient temperature for a clear sky condition at Kenyatta University

4.11 Economic analysis

The dryer was assumed to operate daily through out the year (365 days) drying one batch daily of 20kg o fresh tomatoes consuming 6kg LPG gas cylinder. The annual capital cost of the LPG dryer was calculated to be ksh 781,900. The total amount of dried product processed in this LPG dryer per year was 547.5kg, and the cost of producing 1kg of dried tomatoes turned out to be ksh 1,253.33. At a selling price of ksh 1,925 per kg of dried tomatoes the revenue obtained per every kilogram of dried tomatoes was ksh 672.67. Table 4.10 shows the calculated value of the annual saving, the present worth of the annual saving and the cumulative present worth of the annual saving for each year of the LPG dryer in the case of tomato drying.

Table 4.6 Annual saving, present worth of annual saving and present worth of cumulative annual saving for each year during the life of the LPG dryer for drying tomatoes

Year	Annualized cost of dryer	Annual savings	Present worth of annual saving	Present worth of cumulative saving
1	682,300.00	371,637.50	314,947.03	314,947.03
2	682,300.00	371,637.50	266,904.27	581,851.30
3	682,300.00	371,637.50	226,190.06	808,041.36
4	698,300.00	355,637.50	183,433.87	991,475.22
5	682,300.00	371,637.50	162,446.18	1,153,921.40
6	682,300.00	371,637.50	137,666.25	1,291,587.65
7	682,300.00	371,637.50	116,666.31	1,408,253.96
8	698,300.00	355,637.50	94,613.15	1,502,867.11
9	682,300.00	371,637.50	83,787.93	1,586,655.04
10	682,300.00	371,637.50	71,006.72	1,657,661.76
11	682,300.00	371,637.50	60,175.19	1,717,836.95
12	698,300.00	355,637.50	48,800.41	1,766,637.36
13	682,300.00	371,637.50	43,216.88	1,809,854.24
14	682,300.00	371,637.50	36,624.48	1,846,478.72
15	682,300.00	371,637.50	31,037.69	1,877,516.41
16	698,300.00	355,637.50	25,170.71	1,902,687.12
17	682,300.00	371,637.50	22,290.79	1,924,977.91
18	682,300.00	371,637.50	18,890.50	1,943,868.40
19	682,300.00	371,637.50	16,008.90	1,959,877.30
20	682,300.00	381,637.50	13,931.92	1,973,809.22

The cumulative present worth of the annual savings for drying tomatoes over the life of the LPG dryer turned out to be ksh 1,973,809.22. The investment for the LPG dryer was ksh 100,000 and lies within the first year. The calculated payback period was 0.359 years (equivalent of 131 drying days). Sreekumar *et al.* (2008) reported the payback period of a solar cabinet dryer for drying bitter gourd (*Momordica charantia*) as 3.26 years equivalent to 815 days of drying.

4.12 Efficiency of the LPG dryer

Five types of efficiencies were calculated as shown in Appendix E. The efficiency of the LPG dryer based on the drying air, exit air and ambient air temperature was 7.87%. The efficiency obtained by comparing the heat stored in boiler water against latent heat of vapoarization and the total heat (sensible plus latent) were 55.52% and 57.29% respectively.

By considering the energy contained in 6kg of LPG, the effieciency of the LPG dryer was 11.04% and 11.40% for latent heat of vaporization only an the total heat (sensible plus latent) supplied to the tomatoes respectively. Mastekbayeva et al. (1999) reported the efficiency of a solar-biomass hybrid dryer while drying earlobe mushrooms as 17.2, 16.8 and 14.4% while operating on solar only, biomass only and hybrid respectively.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

a) A LPG powered dryer can be constructed from locally available materials such as timber, ply wood, waste wool blanket, galvanized iron sheets and pipes, domestic hot water storage tank, electrical fans, battery and solar panels.

b) High quality and aesthetically appealing dried tomatoes can be produced from a LPG powered dryer. The LPG dyer has the advantage of creating uniformly distributed high temperatures and fast movement of air by use of fans. This increases the rate of drying, therefore reducing the risk of spoilage by micro-organisms.

c) The LPG dryer has the ability to extend the drying process while drawing energy from the thermal storage after the LPG burner has been switched off. This makes its more reliable than a solar only dryer whose drying process is weather dependent.

d) The short payback period makes the dryer economically attractive to farmers. In addition, since most farmers keep livestock, it is hoped that many would adopt it with the hope of replacing LPG with biogas thereby reducing the overall operation cost.

5.2 Recommendations

From the economic analysis, the major operation cost of this dryer was the cost of fuel which stood at Ksh 335,800 ($ 4,197.5) per year. This totalled to Ksh 6,716,000 ($ 83,950) over the useful life of the dryer (i.e 20 years). Any reduction in the cost of the fuel will not only translate into tremendous financial savings but will furthet shorten the payback period. In an attempt to reduce the cost of energy, the following three recommendations for further research have been proposed;

a) Incorporate a solar water heater to the boiler system so as to preheat the boiler water during the day time. This would greatly reduce or eleiminate the 2 hours of preheating the boiler water using LPG and therefore save on the cost of LPG.

b) Since LPG can be substituted with biogas, the performance of a biogas powered dryer should be investigated. The adavantage of the biogas system is that apart from the capital cost of the digester, the production of biogas will almost be free. The construction of the digesters will not only create employment but will also offer an effective method of solid waste management. Furthermore, the sludge produced is a good fertilizer.

c) The temperature of the exhaust flue gas was 191.4^{o}C. There is need to explore a method of recovering heat from the flue gas channelling it into the drying chamber. This would make the drying process start immediately the burner is lit. When the boiler water temperature reaches the desired value, the burner can be switched OFF and let the system draw energy from thermal storage. This will reduce the total time the burner is ON from 9.5 hours to just about 4 hours to dry one batch of 20kg of fresh tomatoes.

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APPENDICES

APPENDIX A: RELEVANT DATA FROM LITERATURE

Table A-1 Export volumes for fresh fruits, vegetations and cut flowers 1992-2003 (tons)

Year	Fruits	Vegetables	Cut Flowers	Total
1992	11,232.90	26,323.60	19,806.00	57,363.00
1993	11,697.40	26,785.70	23,635.90	62,119.00
1994	13,079.00	26,978.00	25,121.00	65,178.10
1995	13,865.00	32,126.30	29,373.50	71,758.10
1996	16,869.40	32.742.00	35,212.25	84,523.00
1997	17,450.00	30,880.00	35,850.00	84,180.00
1998	11,350.00	36,800.00	30,220.00	73,370.00
1999	15,595.00	46,377.00	36,992.00	98,964.00
2000	15,415.80	45,038.72	38,756.66	99,211.20
2001	22,595.45	34,770.88	41,396.01	98,762.35
2002	22,482.23	46,479.47	52,106.70	121,068.42
2003	23,575.47	48,674.16	60,982.89	133,232.52

Source: HCDA (2004)

Table A-2 Export values for fresh fruits, vegetations and cut flowers 1992-2003 (million kshs)

Year	Fruits	Vegetables	Cut Flowers	Total
1992	358.98	909.70	1,247.81	2,516.49
1993	489.40	1,700.30	2,482.80	4,672.50
1994	536.60	1,797.45	2,637.18	4,971.23
1995	617.34	2,204.83	3,642.32	6,464.49
1996	769.52	2,577.11	4,366.32	7,701.95
1997	805.11	3,116.18	4,887.75	8,809.03
1998	819.53	4,052.22	4,856.93	9,728.68
1999	1,256.00	5,713.00	7,235.00	14,204.00
2000	1,098.00	5,293.40	7,165.00	13,557.80
2001	1,559.80	8,034.50	1,0626.90	20,221.00
2002	1,461.60	10,471.21	1,4742.30	26,725.11
2003	1,752.65	10,591.41	1,6495.53	28,839.58

Source: HCDA (2004)

TABLE A-3 Maximum water loss for fruits and vegetables before are rendered unsealable

Commodity	Tomato	Cabbage	Carrot	Cucumber	Lettuce	Potato	Green pepper
Water loss (%)	7	7	8	5	3	7	7

Source: Thanh (2006)

Table A-4 Classification of tomato products

Product Name	(ºBrix) Solid content (%)	Temperature (ºC) at Sea level	Other ingredients.
Paste	40	101	-
Puree	34	100	-
Jam	68 – 70	106	Pepcin, sugar, acid
Chutney	42	101	Vinegar, salt, spices
Ketchup	35	100	-
Soup	16	100	Flour, salt, sugar

Source: ITDG (2006)

Table A-5 Classification of dried tomatoes according to their moisture content

Moisture Designation	Minimum moisture (%)	Maximum moisture (%)	Texture
High	25	50	Soft and pliable
Regular	18	25	Firm but pliable
Reduced	12	18	Very firm
Low	6	12	Hard and brittle.

Source: United Nations, 2005

Table A-6 Steam table – Saturated table (temperature table)

Temperature (^oC)	Pressure (kPa)	Enthalpy (sat. vap.) ($kJkg^{-1}$)	Latent heat ($kJkg^{-1}$)	Specific volume (m^3kg^{-1})
0	0.611	2501	2501	206
1	0.66	2503	2499	193
2	0.71	2505	2497	180
4	0.81	2509	2492	157
6	0.93	2512	2487	138
8	1.07	2516	2483	121
10	1.23	2520	2478	106
12	1.4	2523	2473	93.8
14	1.6	2527	2468	82.8
16	1.82	2531	2464	73.3
18	2.06	2534	2459	65.0
20	2.34	2538	2454	57.8
22	2.65	2542	2449	51.4
24	2.99	2545	2445	45.9
26	3.36	2549	2440	40.0
28	3.78	2553	2435	36.6
30	4.25	2556	2431	32.9
40	7.38	2574	2407	19.5
50	12.3	2592	2383	12.0
60	19.9	2610	2359	7.67
70	31.2	2627	2334	5.04
80	47.4	2644	2309	3.41
90	70.1	2660	2283	2.36
100	101.35	2676	2257	1.673
105	120.8	2684	2244	1.42
110	143.3	2692	2230	1.21
115	169.1	2699	2217	1.04
120	198.5	2706	2203	0.892
125	232.1	2714	2189	0.771
130	270.1	2721	2174	0.669
135	313	2727	2160	0.582
140	361.3	2734	2145	0.509
150	475.8	2747	2114	0.393
160	617.8	2758	2083	0.307
180	1002	2778	2015	0.194
200	1554	2793	1941	0.127

Source J. H. Keenan *et al.*, Steam Tables - lnternational Edition in Metric Units,

John Wiley, New York, 1969.

Table A-7 Thermal conductivity of some selected materials

Material/substance	**Thermal conductivity -k- (Wm/k)**
Air	0.024
Aluminium	250
Bitumen	0.17
Carbon	1.7
Cement, Portland	0.29
Cement, mortar	1.73
Chalk	0.09
Concrete, stone	1.7
Copper	401
Iron	79.5
Cotton wool insulation	0.029
Wood	0.12-0.04
Earth dry	1.5
Fibre glass	0.04
Fireclay brick 500^{o}C	1.4
Foam Glass	0.042

APENDIX B: PRELIMINARY EXPERIMENTAL DATA

Table B-1 Thermocouple calibration data

Time (minutes)	**Mercury bulb (°C)**	**K-type (probe) (°C)**	**K-type (junction) (°C)**
0	0	0	0
5	10	9.9	10.2
10	19	18.5	18.7
15	36	34.5	35.1
20	51	50.4	50.8
25	60	60.2	60.7
30	66	66.3	66.7
35	70	70.4	70.5
40	72	72.4	72.6
45	74	74.5	74.3
50	75	75.3	75.7
55	75	75.3	76.0

Table B-2 Temperature values along the height of the dryer

Airflow (m^3/s)	Average temperature Tray no. 1 (6cm from bottom wall) (°C)	Average temperature Tray no. 3 (20cm from bottom wall) (°C)	Average temperature Tray no. 5 (34cm from bottom wall) (°C)	Average Drying bin Temperature (°C)
0.19	55.6	56.4	57.2	56.4
0.23	54.4	54.8	55.1	54.8
0.28	52.0	52.8	53.3	52.3
0.43	49.5	50.5	51.2	50.5

Table B-3 Temperature values along the height of the dryer

Airflow (m^3/s)	Average dryer inlet temperature (^oC)	Average dryer centre temperature (1 m from inlet) (^oC)	Average dryer exit temperature (2 m from inlet) (^oC)	Average Drying bin temperature (^oC)
0.19	57.1	51.8	53.8	56.3
0.23	54.4	53.3	55.1	54.2
0.28	52.5	55.5	56.6	52.7
0.43	51.2	49.5	50.6	50.4

Table B-4 Weight reduction of tomato specimens with time

Local time	**Left top tray**	**Left Middle tray**	**Left Bottom tray**	**Right Top tray**	**Right middle tray**	**Right bottom tray**	**Sun dried tray**
11.36	240.6	218.3	201.1	205.3	227.3	227.4	198.1
12.36	202.2	183.6	168.6	150.5	187.7	182.5	171.3
13.36	168.4	152.7	137.9	114.3	152.1	140.6	144.2
14.36	131.2	123.2	107.1	78.8	115.5	100.7	122.7
15.36	95.4	94.1	78.8	52.4	83.9	65.8	102.6
16.36	69.4	68.0	55.5	36.5	59.9	43.1	86.8
17.36	49.0	48.4	38.7	27.0	42.2	30.7	73.5
18.36	36.5	35.1	29.1	22.3	31.2	24.1	65.5
19.36	28.8	26.2	23.9	20.0	25.5	21.1	65.5
20.36	24.6	21.6	21.3	18.9	22.3	19.6	65.5
21.36	18.9	16.9	17.1	16.9	18.3	17.9	65.5

Table B-5 Initial weight, oven dry weight and initial moisture content of tomatoes

Sample	**Initial weight of tomatoes (gm)**	**Final weight of oven dried tomatoes (gm)**	**Moisture content (%)**
Left top tray	240.6	15.1	93.7
Left middle tray	218.3	12.6	94.2
Left bottom tray	201.1	13.6	93.2
Right top tray	205.3	14.1	93.1
Right middle tray	227.3	14.2	93.7
Right bottom tray	227.4	14.8	93.5
Sun-dried	198.1	10.5	94.7
Total	1818.1	94.9	93.7

Table B-6 Calculated moisture reduction of tomato specimens with time

Local time	**Left top tray**	**Left Middle tray**	**left Bottom tray**	**Right Top tray**	**Right Middle tray**	**Right Bottom tray**	**Sun dried tray**
11.36	93.7	94.2	93.2	93.1	93.7	93.5	94.7
12.36	92.5	93.1	91.9	90.6	92.4	91.9	93.9
13.36	91.0	91.7	90.1	87.7	90.6	89.5	92.7
14.36	88.5	89.8	87.3	82.1	87.6	85.3	91.4
15.36	84.2	86.6	82.7	73.1	83.0	77.5	89.8
16.36	78.2	81.5	75.5	61.4	76.1	65.7	87.9
17.36	69.2	74.0	64.9	47.8	66.1	51.8	85.7
18.36	58.6	64.1	53.3	36.8	54.2	38.6	84.0
19.36	47.6	51.9	43.1	29.5	43.9	29.9	84.0
20.36	38.6	41.7	36.2	25.4	35.9	24.5	84.0
21.36	**20.1**	**25.4**	**20.5**	**16.6**	**21.9**	**17.3**	**84.0**

Table B-7 Boiler system temperatures during no-load heating

Time		**Temperature (ºC)**					
Local Time	**Hour**	**Ambient**	**Boiler water**	**Boiler metal clad**	**Boiler outer surface**	**Burner flame**	**Exhaust Flue gas**
07.12	0.00	20.5	22.9	21.9	20.2	1205	120
07.27	0.25	20.3	28.7	24.5	20.3	-	-
07.42	0.50	20.6	33.5	27.5	20.8	-	-
07.57	0.75	20.5	38.5	30.6	21.4	-	-
08.12	1.00	20.2	43.2	33.9	22.2	1228	198
08.27	1.25	20.5	47.8	37.3	23.2	-	-
08.42	1.50	20.9	52.4	40.6	24.2	-	-
08.57	1.75	20.8	56.8	43.9	25.1		
09.12	2.00	21.0	61.2	47.2	26.0	1233	207
09.27	2.25	21.3	65.4	50.3	26.8	-	-
09.42	2.50	21.4	69.5	53.5	27.8	-	-
09.57	2.75	21.6	73.6	56.6	28.7	-	-
10.12	3.00	21.8	77.6	59.7	29.5	1237	214
10.27	3.25	22.2	81.5	62.7	30.3	-	-
10.42	3.50	22.4	85.2	65.7	31.2	-	-
10.57	3.75	22.8	88.9	68.3	31.7	-	-
11.12	4.00	23.0	92.5	71.1	31.7	1235	218
11.27	4.25	23.1	96.0	73.8	31.7	-	-

APPENDIX C: LPG DRYER DESIGN CALCULATIONS

C-1 Mass of water to be expelled from 100kg of tomatoes

A load of 100kg of tomatoes was considered. Flesh tomatoes have moisture content of about 94% (Barb, 1985; Scharnow, 1986). Dried tomatoes have 6% moisture content when completely dry. The moisture content of the tomatoes will typically be reduced from 94% to 6%. Excell (1980) gives a procedure for calculating the amount of water that can be removed by the airstream as follows,

$M_W = M_C [(W_1-W_F)/ (100-W_F)]$

Where W_1 is the initial moisture content

W_F is the final moisture content

and M_C is the initial mass of the crop

Both W_1 and W_2 are taken on a wet basis.

M_W is therefore 100 [(94-6)/ (100-6)] = 93.62kg

Heat of vaporization of water at 1 atmosphere = 2.257 MJ/kg

Therefore total heat needed to remove 93.62kg of water = 2.257 x 93.62

= 211.3 MJ = 58.69 kWh

Also assuming a drying temperature of 55^{o}C and specific heat capacity of tomatoes as 3.98KJ/kg^{o}C (Engineering Tool Box), the heat required to raise the temperature of the tomatoes in the chamber from room temperature of 15^{o}C to 55^{o}C was calculated from

$$Q = M_c C_c \Delta T_c = 100 \text{ x } 3.98 \text{ x } 40 = 15.92 \text{ MJ } (4.42 \text{ kWh})$$

Therefore, total heat required to dry 100kg of tomatoes was estimated to be 227.22 MJ (63.11kWh).

C-2 Determination of the volume of boiler/storage system

From B-1 above, total required was 227.22MJ. Taking the specific heat capacity of water as 4.2KJ/kg^{o}C, and assuming that the temperature of water will be raised from 15^{o}C to 100^{o}C, the mass of water to store this energy was calculated as

$$M_s = \frac{Q}{Cp_w \Delta T_w} = \frac{227.22 \text{ x } 1000}{4.2 \text{ x } 85} = 636.5\text{kg}$$

Approximately 637 litres of water were required since the density of water is 1000kg/m^3. However, the thermal mass of the of the boiler, heat exchanger and the pipe work all which were made of galvanised iron, would also absorb and store heat energy, and therefore the mass requirement of water was to be less. Also, only part of the drying duration was to depend on the thermal storage alone, while the initial drying period was to take place with the burner ON. A 225 litre storage water heater was therefore chosen. The total volume of the water in the system was about 300 litres (including the expansion tank, the hot water riser and cold water return pipe)

C-3 Airflow requirements

As the system was meant to operate in all weathers the temperature and relative humidity of ambient air entering the heat exchanger were assumed to be 15^{o}C (db) and 90% respectively. Using psychrometric chart, the humidity ratio (mixing ratio) was obtained as 0.0096kg water/kg dry air. The temperature of air leaving the heat exchanger was assumed to be 55^{o}C while its humidity ratio remained constant at 0.0096kg of water/kg dry air. The relative humidity obtained from the psychrometric chart was 9.7%. The relative humidity of air exiting the drying chamber was assumed to be 75% which is the limit beyond which growth of moulds occur. The corresponding dry bulb temperature and humidity ratio were 30^{o}C and 0.0202kg of water/kg of dry air. The increase in humidity ratio of the drying air was calculated as,

$$0.0202 - 0.0096 = 0.0106 \text{ kg of water/kg of dry air}$$

From the gas laws; $PV_a = M_aRT$

Where P is the atmospheric pressure = 101.3 kPa

V_a is the volume of air in m^3.

M_a is the mass of the air in kg

T is the absolute temperature in Kelvin, and

R is the specific gas constant = 0.287 kPa m^3/kgk

For a humidity increase of 0.0106kg water/kg dry air, each 1 kg of water will require;

$$1/0.0106 = 94.34 \text{ kg of dry air.}$$

Therefore total mass of dry air required by 93.62kg of water is given by

93.62 x 94.34 = 8832.1kg of dry air.

For this calculation, the absolute temperature is 30 + 273 = 303K.

Therefore, volume of air needed to remove 93.62kg of water is

$$V = \frac{M_A RT}{P} = \frac{8832.1 \times 0.287 \times 303}{101.3} = 7581.92\text{m}^3$$

C-4 Minimum fan size requirement

For a drying time of 12 hour, there are 12 x 3600 = 43200 seconds.

Airflow rate is therefore $= \frac{7,581.92}{43200} = 0.176\ \text{m}^3/\text{s}$

Neglecting the pressure drop across the drying bed, then,

The minimum fan size = 0.17 x 2118.9 = 370.8 CFM

Two types of fans were locally available in the electronic shops.

Type 1

TA 450DC series MODEL B31873 – 16A from NIDEC BETA OF USA with a voltage and current rating of 12V and 0.280 respectively and a power rating of 3.36 W.

From the manufactures data, the maximum airflow was (0.037 m^3/s) or 80 CFM.

Number of fans required $= \frac{370.1}{80} = 4.6$ (approximately 5 fans).

Total power required = 5 x 3.36 = 16.8W.

Type 2

Model AFB1212SH from Delta electronics of China. This had a voltage and current rating of 12V and 0.9A respectively and power rating of 10.8W. From the manufactures data, the maximum airflow was (0.053 m^3/s) or 113.11CFM.

Number of fans required = $\frac{370.1}{113.1}$ = 3.27 (approximately 4 fans).

Total power required = 4 x 10.8 = 43.2W.

C-5 Battery bank and PV panel sizing

So as to meet the power requirements of any model of the fans described in B-3, the system battery bank and solar panel were sized based on fan Model AFB1212SH from Delta electronics of China. Also, to cater for pressure drop across the heat exchanger and the drying chamber, the number of fans was increased from 4 to 6.

Thus total power requirement was given by = 10.8 x 6 = 64.8W

Operating voltage of the fans = 12V.

Assuming a drying period of 12 hours,

Total Watt hour per day = 64.8 x 12 = 777.6Wh

Assuming a battery efficiency of 80%, then total storage required is

777.6/0.8 = 972Wh.

Assuming a battery temperature of 15°C, the compensating factor is 1.11

Therefore total storage required is 972 x 1.11 = 1078.92Wh.

Required battery bank Ampere hour = 1078.92/12 = 90 Ah

To cater for drying operations on a cloudy day a choice of double the requirement is preferred. Thus a battery of 200Ah was chosen.

Solar panels charging voltage is between 17 V to 17.5 V.

The panel chosen must provide 777.6Wh daily or 777.6/17 = 45.74Ah daily.

Assuming an average of 8 hours of bright sunshine daily,

The solar panel charging current requirement is = 45.74/8 = 5.72 A.

Rating of PV-Solar panel = Charging voltage x Charging Current

= 17 x 5.72 = 97.24W.

Therefore a 100W solar panel was required to provide enough power for daily operation. However, it would take a minimum of two days to fully charge the battery.

C-6 Circulating pressure

The system was designed to operate as a gravity/thermosiphon hot water system utilizing natural convection forces instead of a water pump for water circulation. The average hot water flow out of the boiler and cooled return water temperatures back to the boiler were taken as 60°C and 50°C respectively and using Table B-1, this represented a circulating pressure of 39 N/m^2

Table C-1 Circulating Pressure in Pa (N/m^2) per metre circulating elevation

Return cooled water Temperature (°C)	Hot water flow Temperature (°C)							
	95	90	85	80	75	70	65	60
50	257	223	190	159	129	101	74	39
55	232	200	168	136	106	97	50	24
60	209	176	143	112	82	53	26	-
65	183	150	117	87	56	27	-	-
70	156	123	90	59	28	-	-	-
75	127	94	61	30	-	-	-	-
80	98	64	31	-	-	-	-	-
85	66	32	-	-	-	-	-	-

Source: Engineering ToolBox, 2005 (www.engineering ToolBox.com)

C-7 Energy requirement in the heat exchanger

Mass flow rate of air = $\frac{8832.1}{43200}$ = 0.204kg/s

Inlet temperature of ambient air to the heat exchanger = 15°C.

Outlet temperature of heated air from the heat exchanger = 55°C.

Energy requirement of the heat exchanger is given by,

$$Q = m_a Cp_a \Delta T_a$$

$$= 0.204 \times 1.006 \times (55 - 15) = 8.21\text{kW}.$$

The circulating water through the heat exchanger was expected to deliver 8.21kW with a temperature difference of 10°C.

$$Q = m_w C_{pw} (T_{w,in} - T_{w,out}) = m_a C_{pa} (T_{a,out} - T_{a,in})$$

The mass flow of water can be expressed as:

$$m_w = \frac{Q}{Cp_w \Delta T_w}$$

$$\frac{8.2}{4.2 \text{ x } 10^oC} = 0.195kg/s$$

The volumetric flow of water was estimated by dividing the mass flow rate of water by the density of water as;

$$\frac{0.195}{1000} = 0.195 \text{ x } 10^{-3} \text{ m}^3/s$$

C-8 Volume of expansion tank

The expansion of water heated from 7^{o}C to 100^{o}C is approximately 4%. To avoid the expansion building up a pressure in the system exceeding the design pressure, a temperature and pressure relieve valve would be required. Also an expansion tank is required in a heating, cooling or air condition system to avoid an unacceptable increase of the system pressure during heat-up. An open expansion tank has the disadvantage of allowing air to enter the system via absorption in the water. As a result, it must be located in the highest point of the system. Required volume of open expansion tanks can be expressed as;

$$V_{et} = 2V_w [(v_1 / v_0) - 1]$$

Where

V_{et} = necessary expansion tank volume (litre)

V_w = water volume in the system (litre)

v_0 = specific volume of water at initial (cold) temperature (m^3/kg)

v_1 = specific volume of water at operating (hot) temperature (m^3/kg)

Volume of the the water in the system (litre) = 300

Density of water at initial (cold) temeperature of 15°C = $1.23 kg/m^3$

Specific volume of water at operating (hot) temperature of 100°C = $0.94 kg/m^3$

$$V_{et} = 2 \text{ x } 300 \text{ x } [(1.059/0.813)-1]$$

$$= 180 \text{ litre tank}$$

However, since the water would only expand by 4% (12 litres), a 40 litre storage water heater tank was used as an expansion tanl.

C-9 Cross-flow Heat Exchanger Design

The heat exchanger is designed from its lower operational limits as follow based on the following assumptions;

Minimum temperature of water entering the heat exchanger = 60°C.

Temperature of the water leaving the heat exchanger = 50°C.

Temperature of ambient air entering the heat exchanger = 15°C.

Temperature of air leaving the heat exchanger = 55°C.

From the conservation of the total mass the total heat transfer between the two streams can be expressed as;

$q = m_w C_{pw} (T_{w,in} – T_{w,out}) = m_a C_{pa}(T_{a,out} – T_{a,in})$

$q = UA\Delta T_{lm}F$

Where

U = Overall heat transfer coefficient.

For an air-cooled heat exchanger with water inside the tube is in the range, U is in the range of

600 –750 W/ (m^2 K)

F = correction factor which is a function of two dimensionless parameters P (effectiveness) and R (capacity ratio)

A = surface area of the heat exchanger.

ΔT_{lm} = Log-mean temperature difference.

Effectiveness, $P = \frac{T_{w,\,out} – T_{w,\,in}}{T_{a,in} – T_{w,in}} = \frac{50 – 60}{15 – 60} = \frac{-10}{-45} = 0.22$

Capacity Ratio, $R = \frac{T_{a,\,in} – T_{a,\,out}}{T_{w,\,out} – T_{w,\,in}} = \frac{15– 55}{50 - 60} = \frac{-40}{-10} = 4$

From the graph of single-pass cross-flow heat exchangers in which one streams unmixed and the other one is mixed, F is approximately equal to 8

$\Delta T_2 = T_{w,in} – T_{a,out} = 60 – 55 = 5^oC$

$\Delta T_1 = T_{w,out} – T_{a,in} = 50 – 15 = 35^oC$

$$\Delta T_{lm} = \frac{\Delta T_2 – \Delta T_1}{Ln\frac{\Delta T_2}{\Delta T}}$$

$$= \frac{(5 - 35)\,^{o}C}{\mathrm{Ln}\,(5/35)} = 15.42^{o}C$$

$$A = q/U\Delta TLmF$$

$$A = \frac{8.21 \times 1000}{600 \times 15.42 \times 0.8}$$

Therefore surface area required = 1.11 m^2

To obtain a higher heat transfer coefficient and allow more heat transfer area, 1 -inch outer diameter pipes was preferred to larger ones and be arranged to form a triangular pitch (Mcketta, 1991). To minimise the flow restrictions and for ease of construction a 1-inch tube will be used.

Therefore total tube length, $L = \frac{A}{\pi D} = \frac{1.11}{3.14 \times 0.0254} = 13.92$ m

Taking the height of the to be 30cm, number of tubes = $\frac{13.92}{0.30}$ = 46.2 tubes

Thus the minimum number of tubes = 47.

C-10 Design of drying chamber

About 7kgs of quartered tomatoes fitted a 100cm by 50cm drying tray (Andritsos, *et al*, 2003) an equivalent of 0.5m^2. Therefore, 100 kg of tomatoes would occupy 7.14m^2. Also 25 trays fitted in a 2m height. This implied a space of 8cm high per tray while keeping the distances from top of the dryer and the first tray and bottom of the drier and the last tray at 4 cm. By limiting the width and length of the drying chamber to 0.6 m and 2 m respectively,

The area of each drying tray = 0.7 x 2 = 1.4m^2.

Therefore, number of drying trays will be $\frac{7.14}{1.4}$ = 5.1

The height of the drying chamber = {(8 x 4) + (2x 4)} = 40cm = 0.40m

APPENDIX D: ECONOMIC ANALYSIS OF LPG DRYER

TABLE D-1 Capital cost of material for construction of LPG dryer (Rates as on year 2008)

Item	Unit cost (Ksh)	Total cost (Ksh)
1 No.225 litre ordinary water storage tank	12,500.00	12,500.00
1 No. 40 litre ordinary water storage tank	4,000.00	4,000.00
4 No. 20 feet 1-inch GI pipe	1,750.00	7,000.00
1 No. Toyota air-conditioning fan	2,500.00	2,500.00
1 No LPG burner	2,000.00	2,000.00
1 No 6kg LPG cylinder with gas and accessories	5,000.00	5,000.00
1 No. Toyota air-conditioning fan	2,500.00	2,500.00
1 No. Toyota radiator cooling fan	2,500.00	2,500.00
1 No. 200Ah Lead acid solar battery	16,000.00	16,000.00
1 No. 10A Solar charge controller	7,000.00	7,000.00
10 metres 2.5mmn flat twin electric wire	50.00	500.00
1 No. 2-inch GI pipe	1,500.00	1,500.00
1 No. 2-inch gate valve	500.00	500.00
2 No. 2-inch bends	200.00	400.00
3 No. 2-inch unions	200.00	600.00
100 feet of 3" by 2"	30.00	2,000.00
1 No. 2mm galvanised iron sheet	1,500.00	1,500.00
2 No. gauge 28 aluminium sheet	1,800.00	1,800.00
2 No. 4' by 8' plywood	400.00	800.00
20kg of wool blanket	30.00	600.00
20kg calcium oxide	20.00	400.00
1 No. 50kg bag of cement	750.00	750.00
1 No. 50kg bag of vermiculite	500.00	500.00
20 metre of chicken wire	100.00	2,000.00
1.5kg of assorted nails	100.00	150.00
Labour plus installation charges	20,000.00	20,000.00
Miscellaneous	5,000.00	5,000.00
Total Cost		**100,000.00**

Table D-2 General assumptions for economic analysis of LPG dryer

Cost of dryer	Ksh 100,000
Dryer service life	20 years
Interest rate	18%
Capacity per batch	20kg
Drying time	11.5 hours
Dryer utilization	365 days (batches)/ year
Initial MC (wet basis)	93.7%
Final Mc (wet basis)	15%
Weight after drying	1.5kg
Price of LPG	Ksh 920 per 6kg cylinder
Labour requirement per batch	1 man day/batch
Labour wage	Ksh 300/day
Cost of tomatoes	Ksh 3/ kg during glut and Ksh 30/kg during the dry season
Selling price of dried potatoes	Ksh 1925/kg
Repair & maintenance	3.2% of investiment
Salvage value	10% of the system cost

Annual variable cost

Item	**Cost (Kshs)**
(a)Labour cost (1 labour per day @ KShs 300 for 365 days)	= 109,500
(b)Average cost for battery replacement	
(4 batteries for 20 years @ KShs 16,000 each)	= 3,200
(c) Fuel cost (6 kg cylinder daily @ KShs 920 for 365 days)	= 335,800
(d) Cost of fresh tomatoes	
(20kg per day @ KShs 30 for 365 days)	= 219,000
Total variable cost	**= 667,500**

Fixed cost of the dryer

Item	**Cost (KShs)**
(a) Cost of the dryer	=100,000

(b) Depreciation at 10@ salvage value;

$$= \frac{\text{Purchase price – Salvage value}}{\text{Number of useful life years}} = \frac{(100{,}000 – 10{,}000)}{20} = 4{,}500$$

(c) Interest on capital @ 18%;

$$= \frac{(\text{Purchase price + Salvage value})}{2} \times \frac{\text{Interest}}{100} = \frac{(100{,}000+10{,}000)18}{200}$$

$$= 9{,}900$$

Total fixed cost of the LPG dryer = 114,400

Therefore, total cost of the LPG dryer
= Fixed cost + variable cost = (667,500 + 114,400) = 781,900

Yearly cost of operation of the LPG dryer
= Depreciation + interest +variable cost = (4,500+9,900+667,500)= 681,900

Annualized cost method

Annualized cost (AC) = (Annual capital recovery (ACR)) + (Annual operation maintenance and repair (AOMR)

Annual capital
recovery (ACR) = Capital recovery factor (CRF) x Capital investment cost (I)

Capital recovery
factor (CRF) = $r /1-(1+r)^{-n}$

Where, r is the annual discount rate; n; the life in number of years

Total cost of LPG dryer = Ksh 100,000

Expected life of the system = 20 years

Discount rate = 18 %

CRF = $0.18/1-(1+0.18)^{-20}$ = 0.187

Therefore, Annual capital recovery (ACR) = CRF x I = 0.187 x 100,000 = 18,700

Annual operation maintenance and repair (A O M R) = 667,500
assumed to be equal to total variable costs

Annualised cost of the LPG dryer = ACR = AOMR = 18,700 + 667,500 = 686,200

Annual output of the LPG dryer (1.5kg for 365 days) = 547.5kg

Therefore, annualised cost for drying 1 kg tomatoes = $\frac{686,200}{547.5}$ = 1253.33.

Selling price per kg of dried tomatoes = Ksh 1925

Net revenue per kg of dried tomatoes = 1925 – 1253.33 = Ksh 672.67

Annual savings = 672.67 x 547.5 = Ksh368, 286.80

APPENDIX E: LPG DRYER EFFICIENCY CALCULATIONS

Energy efficiency in drying is of obvious importance as energy consumption is such a large component of drying costs. Basically it is a simple ratio of the minimum energy needed to the energy actually consumed. But because of the complex relationships of the food, the water, and the drying medium which is often air, a number of efficiency measures can be worked out, each appropriate to circumstances and therefore selectable to bring out special features important in the particular process. Efficiency calculations are useful when assessing the performance of a dryer, looking for improvements, and in making comparisons between the various classes of dryers which may be alternatives for a particular drying operation.

Heat has to be supplied to separate the water from the food. The minimum quantity of heat that will remove the required water is that needed to supply the latent heat of evaporation, so one measure of efficiency is the ratio of that minimum to the energy actually provided for the process. Sensible heat can also be added to the minimum, as this added heat in the food often cannot be economically recovered.

Yet another useful measure for air drying such as in spray dryers, is to look at a heat balance over the air, treating the dryer as adiabatic with no exchange of heat with the surroundings. Then the useful heat transferred to the food for its drying corresponds to the drop in temperature in the drying air, and the heat which has to be supplied corresponds to the rise of temperature of the air in the air heater. So this adiabatic air-drying efficiency, η, can be defined by:

$\eta = (T_1 - T_2)/(T_1 - T_a)$

Where T_1 is the inlet (high) air temperature into the dryer, T_2 is the outlet air temperature from the dryer, and T_a is the ambient air temperature. The numerator, the gap between T_1 and T_2, is a major factor in the efficiency.

The following efficiencies were calculated

(a)) Efficiency based heat input and output, in drying air

$$\eta = (T_1 - T_2)/ (T_1 - T_a)$$

$$= (43.3 – 41.9)/ (43.3 – 25.5)$$

$$= 7.87\%$$

(b) Heat supplied to tomato product

= sensible heat to raise tomato product temperature from 25.5°C to 43.3°C +

latent heat of vaporization.

Now, the latent heat of vaporization corresponding to a saturation temperature of 43.3°C is 2399.1 kJ kg^{-1}

Heat (minimum) supplied/15 kg tomato

$$= 15 \text{ x } (43.3 – 25.5) \text{ x } 3.98 + 13.94 \text{ x } 2399.1$$

= 1,062.66 + 33,443.45

= 34,506.11 kJ

Heat to evaporate water only = 13.94 x 2399.1

= 33,443.45 kJ

Volume of air used = 0.43 x 60 x 60 x 11.5 = 17,082 m^3

The specific heat of air is 1.0 J kg^{-1} $°C^{-1}$ and the density of air is 1.06 kg m^{-3}

Heat given up by air/15 kg tomatoes

= 1.0 x (43.3 – 41.9) x 17,082 x 1.06

= 25,349.69 kJ.

The heat stored in water = 300 x 4.2 x (70.7 – 22.9)

= 60,228 kJ.

Total energy contained in 6.6 kg of LPG = 6.6 x 45,878.56

= 302,798.50 kJ

Therefore;

(a) Efficiency based on energy stored in boiler water and latent heat of vaporisation only:

= (33,443.45)/ (60,228)

= 55.52%

(b) Efficiency based on energy stored in boiler water and the minimum heat supplied (sensible plus latent) supplied to the tomatoes

= (34,506.11)/ (60,228)

= 57.29%

(c) Efficiency based on total energy contained in 6.6kg of LPG (assuming efficiency of the burner is 100%) and latent heat of vaporisation only

= (33,443.45)/ (302,798.50)

= 11.04%

(d) Efficiency based on total energy contained in 6.6kg of LPG (assuming efficiency of the burner is 100%) and the minimum heat supplied (sensible plus latent) supplied to the tomatoes

= (34,506.11)/ (302,798.50)

= 11.40%

APPENDIX F

DRYING PERFORMANCE RAW DATA

Table F-1 Performance data during tests with wet blankets, run 2 Date 10-09-08

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer centre Temp (°C)**	**Dryer exit conditions**			**Dryer average Temp (°C)**	**Storage system Temperatures (°C)**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer Surface**
13.39	0.00	24.7	20.0	64.8	53.1	30.4	19.2	46.4	42.2	29.0	37.2	47.3	80.4	26.9
13.54	0.25	24.6	19.8	64.0	53.1	30.4	19.2	48.3	42.8	29.1	36.0	48.1	79.4	27.0
14.09	0.50	26.1	19.8	58.0	51.2	29.5	19.9	47.4	41.9	28.5	36.3	46.8	74.6	26.5
14.24	0.75	26.3	20.2	57.0	50.1	29.1	20.7	46.4	42.4	28.3	34.2	46.3	71.9	26.6
14.39	1.00	25.4	19.7	58.7	48.0	28.0	21.4	45.0	41.3	27.5	34.3	44.8	68.0	26.1
14.54	1.25	25.1	19.4	58.7	46.8	27.2	21.4	43.2	40.1	27.0	35.8	43.4	65.9	25.8
15.09	1.50	25.5	19.8	58.8	49.1	28.2	20.1	45.2	41.4	27.3	33.3	45.2	68.4	26.2
15.24	1.75	25.4	19.7	58.7	50.9	27.7	16.3	47.0	42.0	25.6	26.2	47.0	69.3	26.3
15.39	2.00	25.4	19.9	60.0	52.2	28.3	15.9	47.8	43.2	28.0	31.2	47.8	70.6	26.4
15.54	2.25	25.1	20.1	63.1	51.5	28.3	16.8	47.4	43.3	28.4	32.3	47.4	69.3	26.3
16.09	2.50	24.9	19.8	62.2	50.2	27.7	17.3	47.1	42.9	28.2	32.6	46.7	67.5	26.1
16.24	2.75	24.9	19.7	61.6	50.4	27.7	17.0	47.3	43.3	28.3	31.9	47.0	68.0	26.0
16.39	3.00	24.9	20.0	63.6	51.3	28.4	17.3	47.5	42.0	29.3	38.9	46.9	69.9	26.2
16.54	3.25	22.4	18.8	72.4	52.0	29.5	18.8	48.9	45.4	29.3	30.2	48.8	71.4	24.5
17.09	3.50	22.8	18.9	69.1	51.8	29.4	18.8	49.2	45.8	29.4	29.6	48.9	71.6	24.5
17.24	3.75	22.1	18.8	73.1	50.7	29.1	19.8	48.5	45.7	29.5	30.1	48.3	70.0	23.8
17.39	4.00	22.3	19.2	74.1	50.2	29.0	20.5	48.4	45.0	30.1	33.7	47.8	68.8	24.1
17.54	4.25	23.2	19.7	72.3	49.1	28.7	21.3	47.8	44.6	30.2	35.0	47.1	66.0	24.9
18.09	4.50	23.1	19.6	72.2	47.3	28.0	22.6	46.3	43.6	29.7	35.9	45.7	63.5	25.0
18.24	4.75	23.1	19.6	72.2	46.1	27.7	24.0	45.4	43.0	29.4	36.9	44.8	61.4	24.9
18.39	5.00	23.0	19.7	73.6	44.8	27.3	25.4	44.3	42.1	29.1	37.9	43.7	59.1	24.8
18.54	5.25	23.1	19.8	73.7	43.7	27.1	27.2	43.3	41.5	28.9	38.9	42.8	57.2	24.7
19.09	5.50	23.1	19.8	73.7	42.5	26.8	28.9	42.3	40.7	28.1	40.9	41.8	55.2	24.6
19.24	5.75	22.8	19.7	75.0	41.2	26.3	30.4	41.1	39.8	27.8	42.3	40.7	53.4	24.4
19.39	6.00	22.8	19.6	74.3	40.2	25.9	31.5	40.2	39.0	27.4	43.3	39.8	51.8	24.3

Table F-1 Performance data during run 2 Date 10-09-08 - continued

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer centre Temp (ºC)**	**Dryer exit conditions**			**Dryer average Temp (ºC)**	**Storage system Temperatures (ºC)**	
Local	**Hrs**	**DB (ºC)**	**WB (ºC)**	**RH (%)**	**DB (ºC)**	**WB (ºC)**	**RH (%)**		**DB (ºC)**	**WB (ºC)**	**RH (%)**		**Boiler water**	**Boiler outer surface**
19.54	6.25	22.7	19.5	75.0	39.2	25.5	32.8	39.3	38.2	27.1	44.4	38.9	50.1	24.1
20.09	6.50	22.6	19.5	74.9	38.2	25.2	27.2	38.3	37.5	26.8	45.6	38.0	48.8	24.0
20.24	6.75	22.6	19.4	74.2	37.3	24.9	28.9	37.5	36.8	26.5	46.8	37.2	47.2	23.8
20.39	7.00	22.5	19.5	75.6	36.4	24.5	30.4	36.6	36.1	26.1	47.8	36.4	46.0	23.7
20.54	7.25	22.4	19.2	74.0	35.5	24.1	31.5	35.7	35.4	25.8	47.6	35.5	44.8	23.5
21.09	7.50	22.4	19.2	74.0	34.6	23.7	32.8	34.9	34.6	25.5	49.3	34.7	43.6	23.4
21.24	7.75	22.3	19.1	74.0	33.9	23.5	34.4	34.1	34.0	25.2	50.3	34.0	42.5	23.3
21.39	8.00	22.2	19.1	74.7	33.1	23.2	42.7	33.4	33.4	24.9	51.3	33.3	41.5	23.1
21.54	8.25	22.2	19.0	73.9	32.5	22.9	43.6	32.8	32.7	24.7	52.8	32.9	40.5	23.0
22.09	8.50	22.2	19.0	73.9	31.9	22.6	44.4	32.2	32.2	24.7	53.9	32.1	39.6	23.0
22.24	8.75	22.1	19.0	74.6	31.3	22.4	45.9	31.6	31.6	24.4	55.0	31.5	38.7	22.8
22.39	9.00	22.1	18.9	73.9	30.7	22.2	47.3	31.0	31.1	24.2	56.3	31.0	37.9	22.7
22.54	9.25	22.0	18.9	74.6	30.2	22.0	48.4	30.4	30.6	23.9	57.0	30.3	37.1	22.6
Average		**23.5**	**19.5**	**69.3**	**43.7**	**26.6**	**26.9**	**42.1**	**39.7**	**27.5**	**40.3**	**41.9**	**58.7**	**24.7**

Table F-2 Performance data during moisture content evaluation test, run 3   Date 18-09-08

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (ºC)**	**Dryer exit conditions**			**Dryer Average Temp (ºC)**	**Storage system Temperatures (ºC)**	
Local	**Hrs**	**DB (ºC)**	**WB (ºC)**	**RH (%)**	**DB (ºC)**	**WB (ºC)**	**RH (%)**		**DB (ºC)**	**WB (ºC)**	**RH (%)**		**Boiler water**	**Boiler outer surface**
11.18	0.00	22.4	19.4	75.6	52.2	27.8	14.8	55.7	53.7	28.7	14.9	53.9	92.1	33.3
11.33	0.25	22.7	19.3	72.7	52.4	28.1	15.2	44.7	42.7	27.7	32.2	46.5	92.3	33.4
11.48	0.50	23.5	19.1	66.0	53.5	28.5	14.7	47.8	44.6	29.4	32.4	48.6	91.9	33.5
12.03	0.75	24.2	19.7	65.8	54.0	28.6	14.3	49.0	45.4	29.8	31.8	49.4	91.6	34.0
12.18	1.00	24.1	19.5	65.0	53.9	28.5	14.2	49.7	45.9	30.0	31.2	49.8	91.4	33.2
12.33	1.25	24.4	19.9	65.9	54.3	28.7	14.2	50.4	46.6	30.2	30.3	50.4	91.1	33.8
12.48	1.50	25.1	19.9	61.7	54.6	28.8	14.0	51.0	47.8	30.5	28.6	51.2	91.5	30.5
13.03	1.75	24.7	20.3	66.8	54.8	28.9	14.0	50.9	47.6	30.2	28.1	51.1	91.9	34.1
13.18	2.00	25.1	20.3	64.4	55.3	29.0	13.6	52.0	48.4	30.5	27.6	51.9	92.1	34.0
13.33	2.25	25.4	20.3	62.6	55.4	29.0	13.5	52.5	48.8	30.6	26.8	52.2	92.0	34.5
13.48	2.50	25.7	20.5	62.2	54.8	29.0	14.2	50.9	47.9	30.9	29.5	51.2	91.9	34.3
14.03	2.75	26.4	20.9	60.8	55.0	29.3	14.5	52.9	49.7	30.7	25.4	52.8	91.7	35.2
14.18	3.00	26.4	20.7	59.6	55.7	29.2	13.6	53.4	50.1	30.8	24.9	53.1	91.8	35.1
14.33	3.25	26.3	20.7	60.1	55.6	29.0	13.3	53.6	50.4	30.7	24.2	53.2	91.2	35.1
14.48	3.50	26.4	20.5	58.3	55.0	29.0	13.9	52.5	50.0	31.1	25.9	52.5	91.0	35.1
15.03	3.75	25.9	20.6	61.7	55.4	29.0	13.5	53.8	51.2	30.7	22.8	53.5	91.2	35.2
15.18	4.00	27.0	20.8	57.0	55.8	29.1	13.3	54.4	52.0	30.9	22.0	54.1	91.3	35.4
15.33	4.25	26.2	20.6	60.0	55.3	28.9	13.4	54.4	52.2	30.9	21.7	54.0	90.1	35.4
15.48	4.50	25.9	20.4	60.4	54.3	28.5	13.8	53.2	51.6	30.8	22.4	53.0	88.3	35.0
16.03	4.75	26.8	20.7	57.4	53.3	28.2	14.3	52.6	51.3	30.3	21.7	52.4	85.2	34.9
16.18	5.00	26.6	20.2	55.4	53.0	27.9	14.1	52.6	51.2	30.1	21.3	52.3	85.4	34.2
16.33	5.25	26.0	19.9	56.7	53.1	27.9	14.0	52.8	51.7	30.0	20.3	52.6	86.2	30.0
16.48	5.50	26.1	19.9	56.1	52.8	27.9	14.3	52.7	51.5	30.6	22.1	52.3	86.8	29.6
17.03	5.75	25.6	19.6	56.9	53.3	27.8	13.5	52.8	52.3	29.9	19.2	52.8	86.9	26.6

Table F-2 Performance data during moisture content evaluation test, run 3   Date 18-09-08 - continued

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer Surface**
17.18	6.00	25.9	19.9	57.2	53.2	27.9	13.9	52.9	52.6	30.1	19.2	52.9	86.8	26.4
17.33	6.25	25.9	19.7	56.0	53.1	27.8	13.8	53.0	52.8	30.1	19.0	53.0	86.3	26.6
17.48	6.50	25.2	19.5	58.5	51.9	27.6	14.8	52.2	51.8	30.2	20.6	52.0	85.6	25.9
18.03	6.75	25.5	19.7	58.1	52.2	27.6	14.4	52.1	52.3	29.6	18.6	52.2	84.4	26.3
18.18	7.00	25.6	19.6	56.9	51.6	27.4	14.8	51.7	51.9	29.6	19.1	51.7	83.2	26.2
18.33	7.25	24.5	19.2	60.6	50.6	27.1	15.4	50.9	51.2	29.4	19.7	50.9	81.6	25.4
18.48	7.50	24.4	19.0	59.8	49.6	26.8	16.1	49.3	50.3	29.4	21.1	49.7	79.8	25.2
19.03	7.75	24.3	19.2	61.7	49.0	26.6	16.4	49.1	49.8	28.9	20.7	49.3	78.0	25.3
19.18	8.00	24.5	19.5	62.6	48.4	26.5	17.1	48.7	49.3	28.8	21.3	48.8	76.1	25.3
19.33	8.25	24.7	19.2	59.4	47.5	26.2	17.7	47.9	48.5	28.6	22.1	47.9	74.1	26.7
19.48	8.50	24.6	19.3	60.6	46.3	25.8	18.6	47.0	47.2	28.6	23.9	46.8	71.6	27.9
20.03	8.75	24.7	19.4	60.7	47.8	26.8	18.7	47.6	48.3	28.7	22.7	47.9	68.0	27.7
20.18	9.00	24.5	19.6	63.3	46.6	26.4	19.6	46.8	47.2	28.4	23.9	47.0	65.4	26.6
20.33	9.25	23.9	19.1	63.5	45.1	25.8	20.6	45.5	46.0	27.9	24.8	45.5	63.3	26.1
20.48	9.50	23.7	19.1	64.7	43.4	25.2	22.1	44.1	44.2	27.6	27.6	43.9	60.8	25.9
21.03	9.75	23.4	19.0	65.9	42.2	24.7	23.0	42.7	43.0	27.5	30.0	42.6	59.0	25.7
21.18	10.00	23.2	18.8	65.7	41.6	24.5	23.6	41.0	42.7	23.5	31.7	41.6	56.8	25.2
Average		**25.1**	**19.8**	**61.6**	**51.8**	**27.7**	**15.5**	**50.5**	**47.9**	**28.9**	**23.7**	**50.5**	**83.6**	**30.5**

Table F-3 Performance data during thermal storage performance test, run 4   Date 25-10-08

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system temperatures (°C)**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**
13.02	0.00	26.5	22.1	68.1	41.8	26.3	28.9	40.1	35.8	24.9	40.9	39.2	73.3	38.9
13.17	0.25	25.7	21.4	68.2	43.9	21.4	11.1	40.1	38.0	26.5	40.2	40.7	73.0	38.7
13.32	0.50	25.1	21.0	69.2	42.9	24.9	22.2	40.3	38.0	26.4	39.8	40.4	68.4	37.6
13.47	0.75	25.9	21.4	67.0	41.5	24.8	24.7	39.6	37.5	26.4	41.4	39.5	65.3	35.8
14.02	1.00	25.7	21.1	66.2	40.3	24.1	25.1	38.8	36.9	26.1	42.2	38.6	61.9	34.6
14.17	1.25	26.9	21.7	39.8	39.8	23.9	25.6	38.3	36.5	25.8	42.3	38.2	58.5	33.4
14.32	1.50	26.5	21.6	64.8	38.6	23.4	26.7	37.3	35.7	25.6	44.2	37.2	56.6	32.5
14.47	1.75	26.6	21.5	63.6	37.6	23.1	28.2	36.5	35.0	25.2	45.0	36.4	53.9	31.7
15.02	2.00	26.1	21.0	63.2	36.4	22.4	28.7	35.4	34.0	24.7	46.4	35.3	52.0	31.0
15.17	2.25	25.8	20.9	64.3	35.4	21.9	29.6	34.6	33.3	24.2	46.7	34.4	49.8	30.2
15.32	2.50	26.5	21.4	63.5	35.2	22.1	30.9	34.7	33.2	24.2	47.1	34.5	48.1	29.9
15.47	2.75	26.9	21.7	63.1	35.6	22.0	32.3	33.9	32.7	24.1	48.7	33.8	46.5	29.5
16.02	3.00	26.6	21.8	65.5	33.9	21.5	32.4	33.2	32.1	23.7	49.2	33.1	45.0	29.2
16.17	3.25	26.1	21.0	63.2	32.9	20.9	32.9	32.4	31.4	23.1	49.0	32.3	43.6	28.6
16.32	3.50	26.2	21.1	63.3	32.5	20.8	33.8	32.0	31.1	22.9	49.3	31.9	42.4	28.3
16.47	3.75	25.7	21.5	68.9	31.8	20.5	34.8	31.4	30.5	22.5	49.8	31.2	41.2	27.9
17.02	4.00	25.6	19.9	58.9	31.3	20.3	35.6	31.0	30.1	22.5	51.6	30.7	40.1	27.6
Average		**26.1**	**21.3**	**63.6**	**37.1**	**22.6**	**28.4**	**35.9**	**34.2**	**24.6**	**45.5**	**35.7**	**54.1**	**32.1**

Table F-4 Performance data during thermal storage performance test, run 5 Date 6-11-08

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**
11.42	0.00	23.7	19.9	70.4	52.1	27.5	14.4	44.6	43.2	24.9	43.6	46.6	97.0	33.3
11.57	0.25	24.1	20.1	69.2	54.1	30.1	17.2	49.3	47.6	30.5	29.0	50.4	95.3	32.6
12.12	0.50	23.6	20.0	71.8	50.7	29.5	20.7	47.7	46.6	30.4	30.9	48.2	87.1	32.6
12.27	0.75	23.8	20.6	74.9	48.7	29.0	22.8	46.6	45.6	30.2	33.3	46.8	81.1	32.1
12.42	1.00	24.3	20.7	72.2	46.9	28.2	23.9	45.1	44.1	29.6	34.3	45.4	77.5	31.4
12.57	1.25	24.3	20.7	72.2	44.7	27.5	26.2	43.5	42.6	29.1	36.5	43.6	72.3	30.8
13.12	1.50	24.3	20.7	72.2	43.3	26.9	27.4	42.2	41.4	28.5	37.7	42.3	69.0	30.1
13.27	1.75	24.5	20.8	71.6	41.7	26.3	29.2	40.7	40.1	27.9	39.2	40.8	64.9	29.7
13.42	2.00	24.1	20.4	71.4	40.2	25.5	30.1	39.4	39.1	27.2	39.6	39.5	62.0	29.2
13.57	2.25	24.2	20.5	71.4	38.8	25.0	32.0	38.2	37.7	26.8	42.5	38.2	58.8	28.7
14.12	2.50	24.3	20.6	71.5	37.7	24.5	33.2	37.2	36.8	26.4	43.8	37.2	56.3	28.4
14.27	2.75	24.9	20.7	68.4	36.7	24.2	36.5	36.2	35.9	25.9	44.8	36.3	53.7	27.9
14.42	3.00	24.4	20.4	69.4	35.6	23.4	35.0	35.2	34.9	25.5	46.7	35.2	51.5	27.6
14.57	3.25	24.7	20.7	69.6	34.9	23.3	36.9	34.5	34.3	25.3	48.1	34.3	49.5	27.3
15.12	3.50	24.8	20.7	69.0	34.0	22.9	38.1	33.7	33.5	24.8	48.9	33.8	47.5	27.1
15.27	3.75	24.4	20.5	70.1	33.4	22.7	39.3	33.0	33.0	24.5	49.4	33.1	46.4	26.9
15.42	4.00	24.5	20.4	68.8	32.4	22.2	40.6	32.2	32.1	24.1	51.2	32.3	44.3	26.6
15.57	4.25	24.9	20.7	68.4	32.1	22.1	39.8	31.8	32.1	23.6	52.6	31.9	42.8	26.4
16.12	4.50	24.7	20.5	68.2	31.4	21.8	42.5	31.2	31.2	23.6	52.6	31.3	41.5	23.2
16.27	4.75	24.7	20.5	68.2	31.1	21.8	43.6	30.6	30.9	23.4	52.8	30.7	40.6	26.0
Average		**24.4**	**20.5**	**70.4**	**40.0**	**25.2**	**31.5**	**38.6**	**38.1**	**26.6**	**42.9**	**38.9**	**62.0**	**28.9**

Table F-5 Performance data during optimization test, run 6 Date 29-11-08

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (ºC)**	**Dryer exit conditions**			**Dryer Average Temp (ºC)**	**Storage system Temperatures (ºC)**	
Local	**Hrs**	**DB (ºC)**	**WB (ºC)**	**RH (%)**	**DB (ºC)**	**WB (ºC)**	**RH (%)**		**DB (ºC)**	**WB (ºC)**	**RH (%)**		**Boiler water**	**Boiler outer surface**
09.07	0.00	21.4	19.0	79.8	37.4	24.1	32.5	32.7	31.9	22.0	41.5	34.0	66.1	22.3
09.22	0.25	22.1	19.1	75.4	38.8	25.6	24.2	36.5	34.7	24.1	41.0	37.0	67.7	22.4
09.37	0.50	21.8	19.3	79.2	40.5	26.0	31.1	38.0	35.1	25.1	44.1	38.3	69.3	22.9
09.52	0.75	22.2	19.3	73.5	41.1	26.3	30.6	38.8	37.3	25.5	38.4	39.1	70.3	23.4
10.07	1.00	22.1	19.4	77.2	41.8	26.6	29.9	39.7	37.9	25.5	36.5	39.8	71.0	23.3
10.22	1.25	22.6	19.4	74.2	42.5	26.9	29.2	40.3	38.5	25.7	35.5	40.4	72.0	23.1
10.37	1.50	22.8	19.4	72.8	43.2	27.1	28.3	41.1	39.3	26.0	34.3	41.2	72.9	23.6
10.52	1.75	23.2	19.3	69.3	43.3	27.1	28.0	41.8	40.0	26.1	32.8	41.9	73.8	23.9
11.07	2.00	23.9	19.8	68.4	44.6	27.6	26.8	43.0	40.9	26.5	31.8	42.8	74.6	24.4
11.22	2.25	24.1	19.9	67.8	45.1	27.7	26.0	43.2	41.5	26.8	31.3	43.2	75.5	24.8
11.37	2.50	24.4	19.8	65.2	45.6	27.9	25.6	43.8	42.2	26.8	29.6	43.9	76.3	25.2
11.52	2.75	23.7	19.5	67.5	45.7	27.9	25.4	44.1	42.5	26.8	28.9	44.1	77.0	24.7
12.07	3.00	24.7	19.8	63.4	46.4	28.2	26.9	44.7	43.3	27.0	27.7	44.8	77.7	25.3
12.22	3.25	24.8	19.8	62.8	46.9	28.4	24.4	45.3	43.9	27.2	27.0	45.4	78.1	25.4
12.37	3.50	24.3	19.5	63.8	47.0	28.4	24.3	45.5	44.2	27.0	25.8	45.6	78.7	31.6
12.52	3.75	24.7	19.9	64.1	47.4	28.7	24.3	46.0	44.9	27.4	25.5	46.1	79.7	31.7
13.07	4.00	24.6	19.8	64.0	47.6	29.0	24.8	46.4	45.3	27.6	25.3	46.4	79.7	31.7
13.22	4.25	24.7	19.7	62.7	47.7	28.9	24.3	46.7	45.2	27.4	23.8	46.8	80.1	31.8
13.37	4.50	25.5	20.5	63.5	49.4	29.8	23.6	49.3	46.9	28.4	24.4	48.5	80.3	32.0
13.52	4.75	24.9	19.9	62.9	49.8	30.0	23.4	49.8	47.4	28.4	23.5	49.0	79.4	31.8
14.07	5.00	24.8	19.9	63.5	47.7	29.8	23.1	47.2	46.6	28.0	23.9	47.2	78.8	31.5
14.22	5.25	24.8	20.3	66.2	49.5	30.3	23.4	49.3	47.5	28.5	23.6	48.8	79.5	31.3
14.37	5.50	24.8	20.3	66.2	50.5	29.6	23.0	50.4	48.6	28.9	22.7	49.8	79.0	31.1

Table F-5 Performance data during optimization test, run 6, Date 29-11-08 - continued

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (^{o}C)**	**Dryer exit conditions**			**Dryer Average Temp (^{o}C)**	**Storage system Temperatures (^{o}C)**	
Local	**Hrs**	**DB (^{o}C)**	**WB (^{o}C)**	**RH (%)**	**DB (^{o}C)**	**WB (^{o}C)**	**RH (%)**		**DB (^{o}C)**	**WB (^{o}C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**
14.52	5.75	24.6	19.4	61.3	49.2	29.2	23.4	49.2	47.8	28.6	23.3	48.8	74.2	30.8
15.07	6.00	25.2	19.4	57.9	48.5	28.4	23.7	47.8	46.7	28.1	24.0	47.4	72.1	30.8
15.22	6.25	25.7	19.6	56.4	46.3	27.9	25.6	46.4	45.4	27.5	24.8	46.1	67.7	30.6
15.37	6.50	25.6	20.2	60.8	44.7	27.2	27.4	44.9	44.1	27.2	26.6	44.6	64.9	30.2
15.52	6.75	25.1	19.8	61.1	43.5	26.8	27.9	43.6	43.0	26.8	27.8	43.7	62.2	29.7
16.07	7.00	24.8	19.8	62.8	42.2	27.4	29.6	42.5	42.0	26.2	28.1	42.2	61.8	29.3
16.22	7.25	25.2	20.2	6.3.1	43.4	27.8	28.8	43.7	43.0	26.4	26.5	43.4	64.6	29.2
16.37	7.50	25.0	20.1	63.7	44.3	27.9	28.0	44.7	43.9	26.9	26.1	44.3	66.7	29.3
16.52	7.75	24.9	19.8	62.2	44.5	27.8	27.9	45.1	44.3	27.0	25.6	44.6	67.2	29.4
17.07	8.00	24.2	19.7	65.8	44.3	27.8	28.0	45.1	44.2	27.2	26.4	44.6	67.1	29.0
17.22	8.25	24.3	19.5	63.8	44.2	27.4	28.2	44.9	44.2	27.1	26.1	44.5	66.7	29.2
17.37	8.50	23.9	19.2	64.2	43.7	27.1	28.1	44.4	43.8	26.8	26.0	44.0	65.8	28.6
17.52	8.75	23.4	18.9	65.2	43.1	26.6	28.5	43.7	43.2	26.4	26.1	43.3	64.7	28.2
18.07	9.00	23.3	18.9	65.8	42.1	26.0	29.2	42.7	42.4	26.0	26.6	42.4	62.7	27.9
18.22	9.25	22.9	18.1	62.6	40.7	25.4	30.6	41.3	41.0	25.6	29.9	41.0	59.6	27.2
18.37	9.50	22.4	18.1	65.8	39.3	24.9	32.1	39.8	39.6	25.0	29.9	39.6	57.2	26.8
18.52	9.75	22.8	18.5	66.1	37.9	24.4	32.2	38.6	38.5	24.7	31.7	38.4	54.9	26.6
19.07	10.00	22.4	18.4	68.0	36.2	24.4	37.1	37.5	37.2	24.5	34.6	37.2	52.5	26.1
Average		**24.0**	**19.5**	**64.6**	**44.3**	**27.5**	**27.3**	**43.6**	**42.4**	**26.6**	**29.0**	**43.5**	**70.5**	**27.8**

Table F-6 Performance data during optimization test, run 7, Date 04-12-08

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**
08.13	0.00	20.3	18.6	85.1	37.0	25.3	38.5	32.8	30.9	22.4	47.5	33.5	64.1	21.1
08.28	0.25	20.7	18.9	84.4	38.3	25.7	36.3	35.0	32.7	23.9	47.7	35.3	65.5	22.0
08.43	0.50	19.9	18.6	88.4	38.6	25.9	36.0	35.9	33.5	24.2	46.0	36.0	66.8	28.4
08.58	0.75	19.8	18.3	86.6	39.1	26.1	35.3	36.5	34.1	24.3	44.1	36.6	67.9	28.3
09.13	1.00	20.9	18.5	79.5	39.8	26.5	34.8	37.4	34.9	24.3	41.2	37.5	68.9	28.5
09.28	1.25	21.5	18.8	77.4	41.0	27.3	34.4	38.3	35.8	24.9	40.8	38.4	69.9	28.7
09.43	1.50	21.3	18.8	78.9	41.5	27.5	33.8	39.0	36.2	25.0	39.8	39.0	70.8	28.9
09.58	1.75	22.3	19.0	71.7	42.3	27.8	32.8	39.8	37.3	25.3	37.5	39.8	71.8	29.2
10.13	2.00	22.4	18.9	71.8	42.7	27.6	31.1	40.3	37.8	25.3	36.0	40.3	72.6	29.3
10.28	2.25	23.2	19.4	70.1	43.6	27.8	29.6	41.2	38.7	25.7	34.9	41.1	73.5	29.7
10.43	2.50	23.3	19.5	77.1	44.2	28.4	30.1	41.9	39.4	26.0	34.1	41.8	74.3	30.0
10.58	2.75	22.3	18.8	71.7	44.1	28.0	29.1	42.0	39.6	25.7	32.4	41.9	75.1	30.0
11.13	3.00	23.2	19.1	67.9	44.8	29.3	31.6	42.7	40.3	26.2	32.3	42.6	75.8	30.2
11.28	3.25	22.8	19.1	70.5	45.1	28.2	27.7	43.2	40.8	26.0	30.4	43.0	76.4	30.4
11.43	3.50	23.4	19.2	67.3	45.5	28.9	28.7	43.7	41.4	26.4	30.2	43.5	77.0	30.5
11.58	3.75	23.5	19.2	66.7	46.0	29.1	28.3	44.1	41.9	26.5	29.4	44.0	77.5	30.7
12.13	4.00	24.7	19.5	61.4	46.6	29.2	27.3	44.8	42.6	26.5	27.7	44.7	78.0	30.9
12.28	4.25	24.0	19.6	66.3	46.9	29.3	27.0	45.2	43.2	27.0	28.0	45.1	78.5	31.1
12.43	4.50	24.4	19.6	63.9	47.2	29.3	26.4	45.6	43.6	26.9	26.8	45.5	79.0	30.9
12.58	4.75	24.4	19.3	61.8	48.9	30.3	25.8	47.6	44.2	27.4	27.0	46.9	79.5	31.0
13.13	5.00	25.5	20.0	60.1	51.4	31.9	25.4	48.8	45.3	28.1	26.8	48.5	80.3	31.1
13.28	5.25	24.4	20.0	66.6	52.0	32.1	24.9	49.7	46.4	28.3	25.1	49.4	81.5	31.4
13.43	5.50	24.7	20.5	68.2	52.5	32.6	25.2	50.4	47.1	28.7	24.9	50.0	81.5	31.8
13.58	5.75	24.7	20.4	67.5	52.2	32.1	24.5	50.3	47.3	28.7	24.5	50.0	80.6	31.8

Table F-6 Performance data during optimization test, run 7, Date 04-12-08 - continued

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (ºC)**	**Dryer exit conditions**			**Dryer Average Temp (ºC)**	**Storage system Temperatures (ºC)**	
Local	**Hrs**	**DB (ºC)**	**WB (ºC)**	**RH (%)**	**DB (ºC)**	**WB (ºC)**	**RH (%)**		**DB (ºC)**	**WB (ºC)**	**RH (%)**		**Boiler water**	**Boiler outer surface**
14.13	6.00	25.3	20.9	67.3	51.9	32.4	25.8	50.3	46.7	28.9	26.2	49.9	79.0	31.2
14.28	6.25	25.1	21.0	69.2	49.8	31.0	26.0	48.9	46.3	28.3	25.3	48.3	74.3	31.0
14.43	6.50	24.2	21.0	68.6	49.7	32.0	28.9	47.5	43.8	27.5	28.2	47.0	71.8	30.6
14.58	6.75	24.5	20.5	69.5	46.6	29.0	26.7	46.1	44.2	27.3	26.7	45.7	68.2	29.9
15.03	7.00	25.0	20.9	69.1	45.0	28.2	27.7	44.6	43.2	26.8	27.3	44.3	65.8	29.8
15.28	7.25	25.2	21.2	70.0	43.8	28.3	31.7	43.5	42.3	26.6	28.7	43.2	62.7	29.6
15.43	7.50	25.3	21.2	69.3	42.4	28.0	33.2	42.2	41.3	26.3	31.2	42.0	60.2	29.0
15.58	7.75	24.5	21.0	73.1	41.2	28.0	36.4	41.0	40.1	25.9	31.8	40.8	57.8	28.2
16.13	8.00	24.4	20.7	71.6	40.2	26.5	33.7	39.9	39.2	25.3	32.0	39.7	57.0	28.1
16.28	8.25	24.4	20.7	71.6	40.9	26.7	32.5	41.0	40.0	25.5	30.6	40.7	60.2	28.2
16.43	8.50	24.9	21.0	70.5	41.6	27.2	32.5	41.7	40.8	25.9	30.5	41.4	60.5	28.2
16.58	8.75	23.9	20.8	73.6	40.8	27.1	34.2	40.8	40.1	25.9	31.8	40.6	58.1	27.7
17.13	9.00	24.0	20.7	74.2	39.3	26.3	35.5	39.3	38.9	25.3	32.8	39.1	55.3	27.9
17.28	9.25	23.8	20.6	74.9	38.3	25.8	36.5	38.4	38.1	25.1	34.3	38.3	53.9	27.7
17.43	9.50	23.7	20.6	75.5	36.9	25.3	38.8	37.3	37.0	24.9	36.8	37.1	51.2	27.7
17.58	9.75	23.3	20.3	76.1	34.5	23.5	39.1	34.9	35.3	23.6	36.8	34.9	49.7	27.4
18.13	10.00	22.9	20.0	76.6	33.4	22.7	39.3	33.8	34.2	23.2	38.8	33.8	47.9	26.2
Average		**23.5**	**19.9**	**72.0**	**43.6**	**28.2**	**31.3**	**42.1**	**40.2**	**26.0**	**32.8**	**42.0**	**68.8**	**29.1**

Table F-7 Performance data during optimization test, run 8, Date 04-03-09

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**		**Solar radiation**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/M^2**
0.945	0.00	20.7	18.1	77.8	37.9	24.6	33.0	34.2	31.1	22.1	45.32	34.4	65.6	25.3	2.37	217.3
10.00	0.25	20.7	18.2	78.6	39.0	25.4	32.9	35.9	32.7	22.8	42.3	35.9	67.1	25.0	1.77	162.3
10.15	0.50	21.8	18.3	71.4	40.1	25.7	31.1	36.9	33.7	23.0	39.6	36.9	68.5	25.3	8.61	789.4
10.30	0.75	22.0	18.3	70.0	41.0	26.0	29.9	37.8	34.5	23.2	37.7	37.8	69.8	25.4	8.27	758.2
10.45	1.00	21.8	18.4	72.1	41.8	26.3	28.9	38.6	35.4	23.5	34.8	38.6	71.0	25.4	1.98	181.5
11.00	1.25	22.5	18.5	68.1	42.5	26.4	27.6	39.4	36.2	23.6	34.0	39.4	72.3	25.7	3.64	333.7
11.15	1.50	22.0	17.9	73.8	43.0	26.4	26.5	39.8	36.6	23.6	32.8	39.8	73.3	24.6	2.18	199.9
11.30	1.75	23.2	18.8	65.7	44.0	26.8	25.6	40.8	37.6	24.0	31.5	40.8	74.3	25.4	10.39	952.6
11.45	2.00	23.4	18.6	63.0	44.5	26.9	24.9	41.4	38.2	24.1	30.3	41.4	75.2	25.1	10.71	981.9
12.00	2.25	22.9	18.3	64.0	44.8	27.1	24.9	41.7	38.6	24.1	29.2	41.7	76.0	24.7	3.85	353.0
12.15	2.50	22.8	17.9	61.8	45.1	27.0	24.0	42.1	39.0	23.8	27.2	42.1	76.6	24.7	4.24	388.7
12.30	2.75	23.5	18.5	61.7	45.8	27.4	23.8	42.7	39.6	24.4	27.8	42.7	77.4	24.9	4.15	380.5
12.45	3.00	23.0	18.7	66.3	46.0	27.7	24.2	43.2	40.2	24.7	27.4	43.1	78.0	24.9	10.85	994.7
13.00	3.25	24.3	19.1	61.1	46.7	27.9	23.4	43.8	40.8	24.6	25.6	43.8	78.5	26.1	10.01	917.7
13.15	3.50	24.5	19.0	59.2	47.2	28.0	22.8	44.3	41.4	24.7	24.6	44.3	79.2	25.9	10.33	947.1
13.30	3.75	24.9	19.0	56.9	47.8	28.2	22.3	44.9	42.0	24.9	24.0	44.9	79.8	26.0	7.93	727.0
13.45	4.00	25.0	19.2	57.7	48.3	29.6	25.1	45.6	42.7	25.9	24.4	45.5	80.4	26.5	10.47	959.9
14.00	4.25	25.2	19.2	59.2	48.7	30.0	25.4	46.0	43.3	26.0	24.6	46.0	80.9	27.0	2.08	190.7
14.15	4.50	25.3	18.6	52.2	48.8	29.8	24.7	46.2	43.6	26.3	24.9	46.2	81.3	26.5	9.54	874.6
14.30	4.75	26.2	19.5	53.1	49.4	30.2	24.6	46.9	44.4	26.7	24.5	46.9	81.9	27.4	9.28	850.8
14.45	5.00	26.3	19.2	50.8	49.8	30.1	23.7	47.4	45.0	27.0	24.2	47.4	82.3	27.5	9.28	850.8
15.00	5.25	26.4	19.0	49.1	50.1	30.0	22.9	47.9	45.6	27.1	23.3	47.9	82.8	27.8	8.64	792.1
15.15	5.50	26.3	18.5	46.6	50.3	30.0	22.6	48.2	46.0	27.3	23.1	48.2	83.1	27.6	7.73	708.7

Table F-7 Performance data during optimization test, run 8, Date 04-03-09 - continued

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**		**Solar radiation**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/M^2**
15.30	5.75	26.4	19.1	49.7	50.5	30.4	23.2	48.6	46.6	28.0	23.9	48.6	83.4	28.2	7.22	661.9
15.45	6.00	26.7	18.6	45.3	50.4	30.3	23.1	48.7	46.8	28.1	23.8	48.6	82.6	27.8	6.46	592.3
16.00	6.25	27.1	19.3	47.5	50.2	30.4	23.7	48.6	47.0	28.4	24.3	48.6	81.4	28.4	6.08	557.4
16.15	6.50	26.4	18.9	48.5	49.2	30.0	24.5	47.9	46.6	28.4	25.0	47.9	79.4	27.8	5.24	480.4
16.30	6.75	26.2	18.4	46.5	48.1	29.4	24.9	47.0	45.9	28.1	25.6	47.0	76.7	27.3	3.95	362.1
16.45	7.00	26.6	18.6	45.8	46.5	28.7	26.1	45.8	44.8	27.3	25.4	45.7	72.8	27.8	4.42	405.2
17.00	7.25	26.3	18.5	46.6	44.7	27.8	27.1	44.1	43.4	27.0	27.5	44.1	68.8	27.5	3.88	355.7
17.15	7.50	26.2	18.5	47.1	43.1	27.2	28.8	42.7	42.2	26.7	29.3	42.7	65.5	27.3	3.25	298.0
17.30	7.75	25.8	18.5	49.1	41.6	26.6	30.4	41.3	40.9	26.3	31.1	41.3	62.4	26.8	2.73	250.3
17.45	8.00	25.7	17.9	46.0	40.2	25.6	30.5	40.1	39.8	25.6	31.5	40.0	59.6	26.7	2.09	191.6
18.00	8.25	25.2	17.9	48.4	38.8	25.1	32.4	38.7	38.5	25.2	33.6	38.7	56.9	26.1	1.44	132.0
18.15	8.50	24.9	17.8	49.3	37.5	24.6	34.1	37.4	37.3	24.7	35.1	37.4	54.6	25.6	0.77	70.6
18.30	8.75	24.4	17.8	51.3	36.2	24.1	36.1	36.2	36.2	24.4	37.3	36.2	52.3	25.1	0.26	23.6
18.45	9.00	24.0	17.9	54.8	35.0	23.7	38.2	35.1	35.2	24.1	39.3	35.1	50.2	26.8	0.07	6.4
19.00	9.25	23.7	17.7	55.1	34.0	23.2	39.5	34.1	34.2	23.6	40.6	34.1	48.2	26.2	0.00	0.00
19.15	9.50	24.1	18.5	58.1	33.3	22.9	40.6	33.4	33.5	23.3	41.7	33.4	46.4	26.9	0.00	0.00
19.30	9.75	24.0	18.6	59.4	32.7	22.7	41.8	32.8	32.8	22.9	42.8	32.8	44.8	26.8	0.00	0.00
19.45	10.00	23.9	18.5	59.3	31.8	22.4	43.9	32.1	32.5	22.7	42.6	32.1	43.2	26.6	0.00	0.00
20.00	10.25	23.9	18.4	58.7	31.1	22.0	44.7	31.3	31.4	22.0	43.4	31.3	41.9	26.4	0.00	0.00
20.15	10.50	23.8	18.5	59.9	30.6	21.7	45.2	30.7	30.8	21.3	43.8	30.7	40.5	26.1	0.00	0.00
20.30	10.75	23.5	18.4	61.0	29.9	21.4	46.6	30.1	30.3	21.5	45.4	30.1	39.3	26.0	0.00	0.00
20.45	11.00	23.6	18.4	60.4	29.5	21.1	46.7	29.7	29.8	21.2	45.9	29.7	38.2	25.7	0.00	0.00
21.00	11.25	23.4	18.2	60.3	29.0	20.8	47.3	29.2	29.3	20.8	45.9	29.2	37.2	25.5	0.00	0.00
21.15	11.50	23.2	18.0	60.1	28.3	20.4	48.2	28.5	28.7	20.4	46.4	28.5	36.3	25.3	0.00	0.00
Average		**24.3**	**18.5**	**57.6**	**41.8**	**26.4**	**30.7**	**40.2**	**38.6**	**24.7**	**32.6**	**40.2**	**66.3**	**26.3**	**4.4**	**402.1**

Table F-8 Performance data during optimization test with dryer loaded with 15kg of tomatoes, run 9, Date 09-05-09

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**		**Solar radiation**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/m^2**
7.00	0.00	20.8	18.7	81.9	36.0	23.2	33.0	30.80	28.4	21.8	55.8	31.70	63.20	22.90	0.28	25.7
7.15	0.25	20.8	18.6	81.1	38.4	24.8	32.3	33.70	30.7	23.5	54.3	34.10	65.50	23.10	0.17	15.6
7.30	0.50	20.2	18.5	85.0	38.7	24.9	31.9	35.10	31.5	24.2	54.4	35.10	67.20	22.90	1.25	114.6
7.45	0.75	20.0	18.5	86.7	39.5	25.3	31.2	36.00	32.3	24.6	53.0	35.90	68.70	23.30	0.61	55.9
8.00	1.00	20.6	18.6	82.7	40.2	25.6	30.5	36.80	32.9	24.9	51.9	36.70	70.10	23.30	3.86	353.9
8.15	1.25	21.1	19.0	82.1	41.3	26.0	29.1	38.00	33.7	25.3	50.5	37.70	71.40	23.90	0.92	84.3
8.30	1.50	21.1	18.9	81.2	41.9	26.6	29.7	38.70	34.3	25.5	49.1	38.30	72.60	23.80	1.67	153.1
8.45	1.75	21.3	19.1	81.3	42.7	27.0	29.1	39.60	35.0	25.9	48.2	39.10	74.10	24.10	5.96	546.4
9.00	2.00	21.9	19.2	77.6	43.6	27.3	28.0	40.50	35.7	26.0	46.0	40.00	75.40	24.60	6.02	551.9
9.15	2.25	22.1	19.4	77.7	44.5	27.6	27.0	41.50	36.3	26.3	45.2	40.80	76.60	24.90	2.25	206.3
9.30	2.50	21.7	19.2	79.1	44.9	27.8	26.7	42.00	36.8	26.4	45.2	41.80	77.70	24.70	1.83	167.8
9.45	2.75	22.6	19.4	74.2	45.7	28.0	25.7	42.90	37.5	26.6	42.3	42.00	78.70	25.10	2.93	268.6
10.00	3.00	23.0	19.5	74.4	46.4	28.3	25.1	43.70	38.2	26.9	41.2	42.80	79.70	25.40	8.81	807.7
10.15	3.25	22.3	19.3	75.5	46.6	28.4	25.0	44.20	38.7	26.9	39.6	43.20	80.60	25.30	2.64	242.0
10.30	3.50	23.7	19.7	69.0	47.5	28.7	24.1	45.20	39.4	27.2	38.6	44.10	81.40	25.70	8.57	785.7
10.45	3.75	23.7	19.6	68.2	48.1	28.8	23.3	46.00	40.9	27.3	34.7	45.00	82.20	26.10	8.83	809.5
11.00	4.00	24.5	19.8	64.6	48.7	29.0	22.8	46.70	41.7	27.5	33.3	45.70	82.90	26.20	9.01	826.0
11.15	4.25	24.6	19.8	64.0	49.2	29.1	22.2	47.40	42.3	27.6	32.1	46.30	83.60	26.50	9.85	903.0
11.30	4.50	25.4	19.9	60.0	49.8	29.2	21.4	48.10	43.1	27.7	30.4	47.00	84.30	26.60	9.69	888.4
11.45	4.75	24.5	19.4	61.9	50.1	29.2	20.9	48.70	43.7	27.6	28.7	47.50	84.90	26.60	9.44	865.5
12.00	5.00	24.8	19.8	62.8	50.6	29.5	20.9	49.30	44.4	28.0	28.4	48.10	85.50	26.90	9.22	845.3
12.15	5.25	25.2	19.7	59.6	50.9	29.4	20.2	49.80	45.0	28.0	27.1	48.60	85.90	27.10	9.38	860.0
12.30	5.50	25.4	19.9	60.0	51.3	29.6	20.0	50.40	45.7	28.4	26.8	49.10	86.30	27.30	10.03	919.6
12.45	5.75	25.7	19.8	57.7	51.6	29.7	19.8	50.80	47.0	28.2	23.7	49.80	86.50	27.40	9.85	903.0

Table F-8 Performance data during optimization test with dryer loaded with 15kg of tomatoes, run 9, Date 09-05-09 - continued

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**		**Solar radiation**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/m^2**
13.00	6.00	25.2	19.8	60.5	51.0	29.6	20.5	50.50	47.0	28.4	24.3	49.50	84.90	27.30	9.67	886.5
13.15	6.25	26.6	20.3	56.0	50.9	29.6	20.6	50.50	47.2	28.5	24.2	49.50	83.40	28.00	10.03	919.6
13.30	6.50	26.0	20.0	57.3	50.6	29.3	20.4	50.30	47.3	28.1	22.9	49.40	83.00	27.90	9.73	892.0
13.45	6.75	26.4	20.1	55.8	49.9	29.2	21.3	49.8	48.6	28.2	20.9	49.4	80.6	28.2	2.38	218.2
14.00	7.00	25.8	20.1	59.1	47.4	28.4	23.5	47.6	47.1	27.6	21.9	47.4	75.0	27.6	6.54	599.6
14.15	7.25	26.5	19.8	53.4	46.1	27.6	23.7	46.3	45.7	27.0	22.8	46.0	71.9	27.7	9.26	849.0
14.30	7.50	26.3	20.2	57.0	44.4	27.1	25.7	44.7	44.2	26.5	24.3	44.0	67.7	27.6	8.75	802.2
14.45	7.75	26.5	20.2	53.9	43	26.6	27.1	43.3	43.1	25.9	24.8	43.1	64.8	27.8	8.90	816.0
15.00	8.00	26.3	20.0	55.7	41.5	25.8	28.0	41.8	41.8	25.4	26.0	41.7	61.5	27.2	7.82	716.9
15.15	8.25	26.3	19.7	53.9	40.3	25.4	29.5	40.6	40.7	25.0	27.2	40.5	59.0	27.3	7.23	662.8
15.30	8.50	26.1	19.8	55.5	39.1	24.6	29.7	39.4	39.5	24.3	27.7	39.3	56.4	24.3	6.64	608.8
15.45	8.75	26.4	20.1	55.8	38.1	24.4	31.7	38.4	38.6	24.0	28.9	38.3	54.1	27.2	6.73	617.0
16.00	9.00	26.2	20.2	57.5	37.1	24.1	33.3	37.5	37.7	23.7	30.1	37.4	52.0	27.2	6.11	560.2
16.15	9.25	26.1	20.1	57.4	36.3	23.6	33.7	36.6	35.9	23.4	34.1	36.3	50.1	27.2	5.35	490.5
16.30	9.50	26.4	20.1	55.8	35.6	23.3	34.6	35.8	35.3	23.1	34.7	35.6	48.4	27.1	1.08	99.0
16.45	9.75	26.2	19.6	53.8	34.8	22.9	35.5	35.0	34.8	22.6	34.2	34.8	46.7	26.9	4.44	407.1
17.00	10.00	26.6	20.1	54.7	34.3	22.7	36.2	34.4	34.3	22.5	35.4	34.3	45.2	26.9	3.67	336.5
17.15	10.25	25.5	19.7	58.1	33.2	22.3	38.2	33.5	33.6	22.1	35.9	33.4	43.8	26.4	0.64	58.7
17.30	10.50	26.0	19.8	56.1	32.8	22.2	39.1	33.0	33.2	21.9	36.4	33.0	42.6	26.5	1.87	171.4
17.45	10.75	25.4	19.5	57.4	32.0	21.7	39.7	32.3	32.6	21.6	36.1	32.3	41.4	26.2	1.15	105.4
18.00	11.00	25.4	19.8	59.3	31.5	21.6	41.1	31.7	32.1	21.4	37.9	31.8	40.2	26.1	0.61	55.9
18.15	11.25	25.0	19.6	60.3	30.9	21.5	42.9	31.1	31.2	21.3	37.1	31.1	39.2	25.8	0.17	15.6
18.30	11.50	24.5	19.4	61.9	30.2	21.1	43.7	30.4	30.8	21.0	40.0	30.5	38.3	25.4	0.01	0.90
Average		**24.4**	**19.6**	**65.0**	**42.5**	**26.3**	**28.5**	**41.3**	**38.7**	**25.4**	**35.5**	**40.8**	**68.0**	**26.0**	**5.4**	**491.3**

Table F-9 Performance data during optimization test with dryer loaded with 15kg of tomatoes, Run 10
Date 15-05-09

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**		**Solar radiation**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/m^2**
07.00	0.00	21.0	18.4	77.9	35.6	24.4	36.4	29.9	28.2	21.0	52.1	31.2	60.6	20.9	0.26	23.8
07.15	0.25	20.4	18.2	80.9	36.9	24.4	35.1	32.9	30.8	23.0	51.1	33.5	63.1	20.9	0.49	44.9
07.30	0.50	20.6	18.3	80.2	38.0	25.0	34.2	34.3	31.9	23.8	50.5	34.7	64.9	20.8	0.83	76.1
07.45	0.75	20.7	18.4	80.2	39.1	25.5	33.0	35.4	32.9	24.4	49.4	35.8	66.6	21.0	1.10	100.8
08.00	1.00	20.9	18.5	79.5	39.9	25.8	30.9	36.3	33.8	24.8	47.7	36.7	68.0	21.4	1.84	168.7
08.15	1.25	21.0	18.6	79.6	40.6	26.1	31.2	37.3	34.6	25.1	46.0	37.5	69.3	21.7	1.63	149.4
08.30	1.50	21.5	18.8	77.4	41.3	26.4	30.5	38.0	35.3	25.5	45.2	38.2	70.4	21.9	1.88	172.4
08.45	1.75	21.5	18.8	77.4	41.9	26.9	30.7	38.8	36.0	25.8	44.0	38.9	71.5	22.0	3.25	298.0
09.00	2.00	21.5	19.0	79.0	42.6	27.6	31.3	39.4	36.6	26.1	43.2	39.5	72.5	23.8	2.05	187.9
09.15	2.25	23.1	19.8	73.7	43.5	28.1	30.8	40.4	37.4	26.4	41.8	40.4	73.5	24.4	4.03	369.5
09.30	2.50	22.8	19.5	73.5	44.0	28.1	29.6	40.9	37.9	26.6	41.0	40.9	74.4	24.5	6.16	564.7
09.45	2.75	22.8	19.2	71.5	44.3	28.2	29.3	41.3	38.6	26.7	39.1	41.3	75.2	24.5	7.15	655.5
10.00	3.00	22.8	19.1	70.5	44.7	28.2	28.4	41.9	39.0	26.8	38.3	41.9	76.0	24.4	7.88	722.4
10.15	3.25	23.3	20.0	73.8	45.6	28.8	28.2	42.8	39.8	27.2	37.4	42.7	76.4	24.6	2.43	222.8
10.30	3.50	23.5	19.8	71.0	46.0	29.0	28.0	43.4	40.4	27.5	36.8	43.2	76.9	25.2	3.50	320.9
10.45	3.75	23.7	20.1	71.9	46.5	29.2	27.5	44.0	41.0	27.6	35.5	43.8	77.3	25.1	2.35	215.4
11.00	4.00	24.5	20.1	66.7	46.8	29.2	26.9	44.4	41.4	27.7	34.4	44.2	77.8	25.0	2.62	240.2
11.15	4.25	23.5	19.5	68.8	46.7	29.1	26.9	44.6	41.7	27.6	33.6	44.3	78.1	25.2	2.74	251.2
11.30	4.50	24.2	20.1	68.6	47.2	29.5	26.8	45.2	42.4	28.1	33.5	45.0	78.5	25.1	4.95	453.8
11.45	4.75	24.7	20.4	67.5	47.5	29.8	26.9	46.0	43.1	28.4	32.8	45.6	78.8	25.8	3.25	298.0
12.00	5.00	24.6	20.3	67.5	47.9	29.8	27.2	46.3	43.7	28.6	31.9	46.0	79.2	25.6	3.43	314.5
12.15	5.25	25.1	20.8	67.8	48.5	30.2	26.4	47.0	44.5	29.0	31.3	46.7	79.5	25.6	3.45	316.3
12.30	5.50	25.8	20.9	64.3	48.7	30.2	26.3	47.4	44.9	28.9	30.1	47.0	79.8	25.0	10.87	996.6
12.45	5.75	26.9	21.6	62.5	48.4	30.6	27.6	48.2	45.9	29.4	29.4	47.8	80.1	26.0	7.67	703.2
13.00	6.00	24.8	20.4	66.9	49.0	30.3	25.6	48.2	46.1	29.2	28.4	47.7	80.4	25.2	5.77	529.0

Table F-9 Performance data during optimization test with dryer loaded with 15kg of tomatoes, Run 10
Date 15-05-09 continued

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**		**Solar radiation**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/m^2**
13.15	6.25	25.8	20.8	63.6	49.0	30.5	26.2	48.6	46.7	29.5	28.0	48.1	80.3	26.2	11.21	1027.7
13.30	6.50	26.7	21.1	60.4	49.4	30.5	25.4	48.8	47.1	29.6	27.4	48.4	79.9	26.7	3.04	278.7
13.45	6.75	25.8	20.4	61.0	49.3	30.3	25.1	48.7	47.3	29.6	27.0	48.4	80.0	26.0	10.46	959.0
14.00	7.00	27.7	21.6	58.2	49.2	30.5	25.8	48.8	47.6	29.8	27.0	47.6	78.5	27.2	9.59	879.2
14.15	7.25	26.7	21.3	61.7	46.8	29.7	28.3	46.8	45.9	29.3	29.1	46.5	72.4	26.9	9.56	876.5
14.30	7.50	26.5	20.9	60.3	45.5	28.9	28.7	45.5	44.8	28.6	29.4	45.2	69.9	26.8	2.10	192.5
14.45	7.75	25.6	20.0	59.5	43.0	27.7	30.7	43.2	42.8	27.6	30.8	43.0	65.6	26.0	8.31	761.9
15.00	8.00	26.0	20.3	59.2	42.1	27.3	31.6	42.2	42.1	27.2	31.2	42.1	63.1	26.3	8.03	736.2
15.15	8.25	26.1	20.4	59.3	40.6	26.8	33.7	40.8	40.8	26.8	33.2	40.7	59.7	26.3	8.47	776.5
15.30	8.50	25.6	20.1	60.2	39.3	26.2	35.1	39.5	39.5	26.2	34.5	39.4	57.4	25.8	2.44	223.7
15.45	8.75	25.0	19.9	62.3	37.9	25.7	37.9	38.2	38.3	25.7	36.1	38.1	54.8	25.3	1.59	145.8
16.00	9.00	25.3	20.0	61.2	36.9	25.2	38.4	37.1	37.3	25.3	39.6	37.1	52.6	25.6	3.57	327.3
16.15	9.25	26.0	20.2	58.6	36.3	24.8	38.7	36.5	36.7	25	38.2	36.5	60.6	26.0	5.13	470.3
16.30	9.50	25.1	20.1	63.1	35.0	24.3	40.9	35.3	35.6	24.5	39.7	35.3	48.7	25.6	4.78	438.2
16.45	9.75	25.5	20.1	60.7	34.4	23.9	41.2	34.6	34.9	24.1	40.3	34.7	47.0	25.7	3.40	311.7
17.00	10.00	24.8	19.5	60.8	33.5	23.3	41.7	33.7	33.9	23.5	41.2	33.7	45.4	25.2	0.81	74.3
17.15	10.25	24.7	19.6	62.1	32.8	23.1	43.4	33.0	33.3	23.2	42.0	33.0	43.9	25.0	0.77	70.6
17.30	10.50	24.6	19.5	62.0	32.0	22.7	44.5	32.5	32.5	22.9	43.6	32.3	42.5	24.8	0.65	59.6
17.45	10.75	24.4	19.3	61.8	31.4	22.3	45.0	31.9	31.9	22.5	43.9	31.6	41.3	24.6	0.39	35.8
18.00	11.00	23.9	19.2	64.2	30.6	22.1	47.2	31.2	31.2	22.3	45.8	30.9	40.0	24.2	0.26	23.8
18.15	11.25	23.6	19.2	66.0	30.0	21.9	48.8	30.5	30.5	22.1	47.7	30.2	38.9	23.9	0.11	10.1
18.30	11.50	23.4	19.1	66.6	29.4	21.7	50.4	29.9	29.9	21.9	49.2	29.7	37.9	23.5	0.00	0.0
Average		**24.1**	**19.8**	**67.5**	**41.6**	**27.0**	**32.9**	**40.2**	**38.7**	**26.2**	**38.1**	**40.1**	**66.2**	**24.7**	**4.0**	**363.3**

Table F-10 Performance data during optimization test with dryer loaded with 15kg of tomatoes, run 11, Date 21-05-09

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**		**Solar radiation**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/m^2**
07.00	0.00	21.7	19.4	80.7	37.8	24.5	32.9	31.6	30.0	22.4	48.8	33.1	64.5	26.9	0.21	19.3
07.15	0.25	21.5	18.8	77.4	39.2	25.3	32.0	34.8	32.6	23.9	48.1	35.6	67.0	27.4	0.26	23.8
07.30	0.50	20.6	18.5	81.8	39.9	25.5	31.4	36.0	33.5	24.5	47.4	36.5	68.5	27.4	0.56	51.3
07.45	0.75	21.3	18.6	77.3	40.6	25.8	30.2	36.8	34.3	25.0	46.7	37.2	69.6	27.7	1.66	152.2
08.00	1.00	21.8	18.8	75.2	41.4	26.1	29.2	37.7	35.1	25.3	45.0	38.1	70.7	27.9	1.55	142.1
08.15	1.25	21.2	18.6	78.1	41.8	26.2	28.6	38.2	35.6	25.9	45.9	38.5	71.6	27.7	0.75	68.8
08.30	1.50	20.6	18.4	81.0	42.1	26.4	28.5	38.8	36.1	25.8	43.7	39.0	72.6	27.3	0.96	88.0
08.45	1.75	20.8	18.5	80.3	42.6	26.5	27.7	39.3	36.7	25.9	42.0	39.5	73.3	27.4	1.37	125.6
09.00	2.00	21.3	18.8	78.9	43.2	26.9	27.6	40.0	37.3	26.3	41.7	40.2	74.1	27.6	1.92	176.0
09.15	2.25	21.6	19.0	48.3	43.8	27.5	28.2	40.7	38.0	26.5	40.2	40.8	74.8	27.7	0.91	83.4
09.30	2.50	21.4	18.7	77.4	44.1	27.6	27.8	41.1	38.4	26.6	39.4	41.2	75.4	27.8	1.04	95.3
09.45	2.75	23.0	19.5	72.1	44.9	28.0	27.3	42.0	39.1	27.0	38.8	42.0	76.0	28.2	2.91	266.8
10.00	3.00	21.6	18.8	76.7	44.8	28.0	27.5	42.1	39.4	27.0	37.9	42.1	76.8	27.7	3.24	297.0
10.15	3.25	21.5	18.6	75.8	45.0	28.0	27.1	42.4	39.8	27.1	37.1	42.4	77.3	27.7	2.00	183.4
10.30	3.50	21.3	18.5	76.5	45.1	28.0	26.9	42.7	40.1	27.4	37.3	42.6	77.8	27.5	1.48	135.7
10.45	3.75	21.2	18.5	77.3	45.3	28.1	26.8	43.1	40.6	27.5	36.3	43.0	78.2	27.6	0.98	89.8
11.00	4.00	21.7	18.8	75.9	45.6	28.3	26.7	43.5	41.1	27.8	36.0	43.4	78.5	27.9	0.40	36.7
11.15	4.15	21.3	18.9	79.7	45.9	28.5	26.7	43.9	41.5	28.0	35.6	43.8	78.9	27.9	0.37	33.9
11.30	4.50	21.3	18.7	78.1	46.0	28.5	26.5	44.2	41.8	28.1	35.1	44.0	79.3	27.9	0.35	32.1
11.45	4.75	21.3	19.0	80.5	46.3	28.9	27.1	44.6	42.5	28.5	34.7	44.4	79.6	28.0	0.63	57.8
12.00	5.00	22.4	19.2	74.0	46.5	29.0	26.9	45.1	43.0	28.7	34.0	44.9	79.9	28.1	1.90	174.2
12.15	5.25	22.5	19.7	77.2	47.1	29.4	26.9	45.7	43.7	29.1	33.6	45.5	80.2	28.6	5.25	481.3
12.30	5.50	22.5	19.7	77.2	47.4	29.4	26.3	46.2	44.3	29.3	32.8	46.0	80.5	28.9	2.98	273.2
12.45	5.75	22.7	19.7	75.7	47.7	29.5	26.0	46.6	44.9	29.4	31.7	46.4	80.8	29.1	2.15	197.1
13.00	6.00	22.5	19.5	75.6	47.8	29.4	25.5	46.9	45.3	29.4	30.7	46.7	81.1	29.3	1.66	152.2

Table F-10 Performance data during optimization test with dryer loaded with 15kg of tomatoes, run 11, Date 21-05-09 continued

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**		**Solar radiation**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/m^2**
13.15	6.25	22.7	19.5	74.2	48.0	29.5	25.4	47.3	45.8	29.6	30.2	47.0	81.3	29.4	2.95	270.5
13.30	6.50	23.3	19.8	72.3	48.3	29.5	24.8	47.7	46.4	29.7	29.2	47.4	81.3	29.8	6.43	589.5
13.45	6.75	23.5	20.1	73.2	48.5	29.7	25.0	48.1	46.9	29.9	28.7	47.8	81.1	30.1	5.29	485.0
14.00	7.00	24.1	20.3	70.2	48.8	29.8	24.7	48.3	47.4	30.1	28.2	48.2	81.0	30.5	4.77	437.3
14.15	7.25	23.9	20.1	70.5	48.5	29.7	25.0	48.3	47.5	30.1	28.0	48.1	80.4	30.5	6.65	609.7
14.30	7.50	24.8	20.6	68.3	47.3	29.3	26.2	47.3	46.7	29.8	28.8	47.1	75.1	30.9	5.97	547.3
14.45	7.75	24.6	20.6	69.6	45.4	28.6	28.1	45.5	45.1	29.2	30.6	45.3	71.8	30.7	5.56	509.7
15.00	8.00	25.0	20.5	66.4	43.7	27.9	29.7	44.0	43.8	28.6	31.7	43.8	67.6	30.5	7.48	685.8
15.15	8.25	26.2	21.2	63.9	42.8	27.5	30.5	43.0	42.9	28.2	32.6	42.9	64.6	30.5	6.77	620.7
15.30	8.50	25.7	20.9	64.9	41.2	26.9	32.5	41.4	41.5	27.7	34.5	41.4	61.4	30.0	6.68	612.4
15.45	8.75	25.5	20.5	63.4	39.9	26.1	33.1	40.1	40.3	26.9	34.9	40.1	58.7	29.7	6.44	590.4
16.00	9.00	25.4	20.3	62.6	38.7	25.6	34.5	39.0	39.2	26.4	36.1	38.9	56.2	29.2	6.12	561.1
16.15	9.25	24.4	19.9	65.9	37.1	25.0	36.9	37.4	37.8	25.8	38.0	37.5	53.8	28.3	4.85	444.6
16.30	9.50	24.9	20.1	64.3	36.3	24.7	38.2	36.6	36.9	25.4	39.2	36.6	51.8	28.3	4.74	434.6
16.45	9.75	24.9	20.0	63.6	35.6	24.3	38.8	35.8	36.2	25.0	39.8	35.9	49.7	28.0	2.23	204.4
17.00	10.00	24.3	19.7	65.2	34.4	23.7	40.3	34.7	35.0	24.5	41.8	34.7	47.9	27.6	1.36	124.7
17.15	10.25	24.4	19.6	63.9	33.6	23.3	41.3	33.9	34.2	24.1	42.8	33.9	46.3	27.3	0.74	67.8
17.30	10.50	24.0	19.4	64.9	32.7	22.8	42.3	33.0	33.3	23.5	43.4	33.0	44.6	27.0	0.35	32.1
17.45	10.75	23.8	19.3	65.5	31.9	22.5	43.9	32.2	32.5	23.2	45.0	32.2	43.2	26.7	0.35	32.1
18.00	11.00	23.9	19.4	65.6	31.3	22.3	45.4	31.6	31.9	23.0	46.4	31.6	41.9	26.5	0.08	7.3
18.15	11.25	23.4	19.3	68.0	30.6	22.1	47.2	30.8	31.2	22.7	47.8	30.9	40.6	26.1	0.04	3.7
18.30	11.50	22.9	19.0	69.1	29.9	21.6	47.6	30.9	30.5	22.3	48.7	30.2	39.3	25.7	0.01	0.9
Average		**22.9**	**19.4**	**72.0**	**42.1**	**26.8**	**31.1**	**40.7**	**39.3**	**26.8**	**38.0**	**40.7**	**68.2**	**28.3**	**2.6**	**240.6**

Table F-11 Performance data during optimization test with dryer loaded with 15kg of tomatoes, run 12, Date 25-05-09

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (ºC)**	**Dryer exit conditions**			**Dryer Average Temp (ºC)**	**Storage system Temperatures (ºC)**		**Solar radiation**	
Local	**Hrs**	**DB (ºC)**	**WB (ºC)**	**RH (%)**	**DB (ºC)**	**WB (ºC)**	**RH (%)**		**DB (ºC)**	**WB (ºC)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/m²**
07.00	0.00	20.5	18.4	81.8	37.0	23.4	30.9	31.1	29.3	21.5	49.8	32.5	64.1	25.4	0.17	15.6
07.15	0.25	20.8	18.0	76.2	38.4	24.3	30.5	34.2	31.9	23.4	48.5	34.8	66.4	25.9	0.25	22.9
07.30	0.50	20.0	17.8	80.7	39.2	24.7	29.8	35.4	32.9	24.0	47.4	35.8	67.9	25.9	0.34	31.2
07.45	0.75	19.8	17.8	82.3	39.9	25.0	29.1	36.3	33.7	24.5	46.6	36.6	69.2	25.9	0.41	37.6
08.00	1.00	19.5	17.4	81.3	40.4	25.2	29.6	36.9	34.3	24.7	45.3	37.2	70.4	25.7	0.53	48.6
08.15	1.25	19.3	17.2	81.2	40.8	25.3	28.0	37.5	34.8	24.9	44.3	37.7	71.3	25.4	0.72	66.0
08.30	1.50	19.8	17.4	79.0	41.4	25.5	27.2	38.2	35.4	25.1	43.0	38.4	72.1	25.5	0.99	90.8
08.45	1.75	19.7	17.6	81.4	42.0	25.8	26.8	38.9	36.1	25.4	41.9	39.0	72.8	25.4	1.39	127.4
09.00	2.00	20.3	17.9	79.2	42.5	26.1	26.7	39.5	36.7	25.7	41.2	39.6	73.6	25.9	1.72	157.7
09.15	2.25	20.8	18.1	77.0	43.2	26.4	26.1	40.2	37.5	26.1	40.2	40.3	74.3	26.1	1.67	153.1
09.30	2.50	21.2	18.5	77.3	43.6	26.7	26.1	40.8	38.1	26.4	39.5	40.8	75.0	26.1	1.31	120.1
09.45	2.75	22.0	18.7	73.0	44.3	26.9	25.3	41.5	38.8	26.7	38.5	41.5	75.6	26.9	1.40	128.4
10.00	3.00	22.0	18.9	74.6	44.7	27.2	25.4	42.1	39.3	26.9	37.8	42.0	76.2	27.1	1.77	162.3
10.15	3.25	22.4	19.1	73.3	45.3	27.4	24.7	42.7	39.9	27.2	37.1	42.6	76.8	27.5	2.41	220.9
10.30	3.50	21.7	18.9	76.7	45.3	27.4	24.7	43.0	40.3	27.3	36.4	42.9	77.3	27.5	3.22	295.2
10.45	3.75	22.4	19.3	74.8	45.9	27.7	24.4	43.7	41.1	27.7	35.6	43.6	77.9	27.9	3.79	347.5
11.00	4.00	23.0	19.4	71.4	46.4	27.9	24.0	44.2	41.7	27.9	34.7	44.1	78.4	28.2	3.66	335.5
11.15	4.15	22.6	19.5	74.9	46.8	28.0	23.5	44.8	42.3	28.1	33.8	44.6	78.9	27.9	3.42	313.5
11.30	4.50	22.8	19.6	74.3	47.1	28.2	23.5	45.2	42.8	28.3	33.2	45.0	79.3	28.1	3.31	303.5
11.45	4.75	24.1	19.9	67.8	47.7	28.4	23.0	46.0	43.5	28.6	32.4	45.7	79.7	28.8	3.21	294.3
12.00	5.00	23.0	19.7	73.6	47.8	28.5	23.1	46.3	44.0	28.8	31.9	46.0	80.2	28.9	4.98	456.6
12.15	5.25	23.6	20.1	72.5	48.2	28.7	22.9	46.8	44.8	29.1	30.9	46.6	80.6	28.8	5.42	496.9
12.30	5.50	24.4	20.3	68.7	48.9	28.9	22.2	47.6	45.6	29.4	30.0	47.4	81.0	29.6	4.39	402.5
13.00	6.00	24.5	20.7	70.9	49.4	29.2	22.1	48.5	46.9	29.8	28.4	48.3	81.7	29.8	4.28	392.4

Table F-11 Performance data during optimization test with dryer loaded with 15kg of tomatoes, run 12, Date 25-05-09 continued

Time		Ambient conditions			Dryer inlet conditions			Dryer Centre Temp (°C)	Dryer exit conditions			Dryer Average Temp (°C)	Storage system Temperatures (°C)		Solar radiation	
Local	Hrs	DB (°C)	WB (°C)	RH (%)	DB (°C)	WB (°C)	RH (%)		DB (°C)	WB (°C)	RH (%)		Boiler water	Boiler outer surface	MV	W/m^2
13.15	6.25	25.4	20.8	66.0	49.8	29.4	21.9	48.9	47.5	30.1	28.0	48.7	81.7	30.6	4.69	430.0
13.30	6.50	26.1	21.1	63.8	50.1	29.4	21.4	49.4	48.1	30.5	28.0	49.2	82.2	30.5	6.75	618.8
13.45	6.75	26.7	21.4	62.4	50.8	29.7	21.0	50.0	49.1	30.7	26.5	50.0	82.9	31.3	9.46	867.3
14.00	7.00	25.6	21.0	66.1	50.9	29.7	20.9	50.3	49.5	30.8	26.0	50.2	83.5	31.2	3.60	330.0
14.15	7.25	24.4	19.9	65.9	50.5	29.5	21.0	50.1	49.6	30.6	25.3	50.1	83.9	30.5	2.34	214.5
14.30	7.50	25.1	20.3	64.4	50.1	29.4	21.4	49.9	49.7	30.4	24.6	49.9	82.2	30.9	7.91	725.2
14.45	7.75	25.5	20.5	63.4	47.9	28.6	23.1	47.9	47.8	29.7	26.3	47.9	76.0	31.1	7.81	716.0
15.00	8.00	25.6	20.7	64.1	46.8	28.7	25.5	46.9	46.9	29.4	27.3	46.8	72.9	29.4	7.81	716.0
15.15	8.25	25.4	20.3	62.6	44.7	27.3	25.6	44.9	45.0	28.5	28.6	44.9	68.6	30.7	2.01	184.3
15.30	8.50	25.2	20.0	61.8	43.0	26.6	27.1	43.2	43.5	27.8	29.8	43.3	65.7	30.2	3.07	281.5
15.45	8.75	25.3	20.1	61.9	41.6	26.1	28.7	41.8	42.1	27.2	31.2	41.8	62.3	29.9	2.60	238.4
16.00	9.00	25.6	20.1	60.2	40.4	25.6	30.0	40.6	41.0	26.8	32.6	40.6	59.7	29.7	5.77	529.0
16.15	9.25	25.2	20.3	63.8	39.2	25.3	32.0	39.4	39.8	26.4	34.4	39.5	57.0	29.4	1.57	143.9
16.30	9.50	25.5	20.2	61.4	38.1	24.7	32.8	38.3	38.8	25.8	35.0	38.4	54.7	29.0	4.53	415.3
16.45	9.75	25.4	20.1	61.3	37.1	24.5	34.9	37.3	37.8	25.6	37.2	37.4	52.5	28.5	3.86	353.9
17.00	10.00	25.0	20.0	63.0	36.0	24.2	37.1	36.3	36.7	25.2	39.0	36.4	50.5	28.1	1.89	173.3
17.15	10.25	24.7	19.9	64.1	34.9	23.7	38.6	35.2	35.7	24.7	40.2	35.3	48.7	27.6	1.36	124.7
17.30	10.50	24.4	19.7	64.6	34.0	23.3	39.9	34.3	34.7	24.3	41.9	34.3	47.0	27.2	1.37	125.6
17.45	10.75	24.2	19.8	66.5	33.1	23.0	41.8	33.4	33.8	23.9	43.4	33.4	45.3	26.9	0.89	81.6
18.00	11.00	23.4	19.6	70.2	32.1	22.8	44.6	32.4	32.8	23.7	46.3	32.4	43.8	26.2	0.41	37.6
18.15	11.25	22.7	19.3	72.7	31.1	22.5	47.2	31.4	31.9	23.4	48.5	31.5	42.4	25.6	0.07	6.4
18.30	11.50	22.5	19.3	74.1	30.4	22.2	48.6	30.7	31.1	23.0	49.8	30.7	41.1	25.3	0.01	0.9
Average		**23.3**	**19.5**	**70.6**	**42.9**	**26.6**	**28.2**	**41.5**	**40.2**	**26.9**	**36.3**	**41.6**	**69.5**	**28.1**	**3.0**	**275.6**

Table F-12 Performance data during optimization test with dryer loaded with 15kg of tomatoes, run 13, Date 30-05-09

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**		**Solar radiation**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/m^2**
07.00	0.00	20.5	18.9	86.0	35.7	23.8	36.4	30.0	28.6	21.6	53.6	31.4	61.8	24.6	0.26	23.8
07.15	0.25	20.0	18.3	85.0	37.3	24.9	35.9	32.9	31.1	23.6	53.0	33.8	64.2	24.5	0.75	68.8
07.30	0.50	20.3	18.3	82.6	38.2	25.2	34.4	34.2	32.1	24.2	51.7	34.8	65.8	25.0	2.13	195.3
07.45	0.75	20.1	18.4	85.0	39.0	25.7	34.1	35.2	33.0	24.7	50.4	35.7	66.8	25.0	0.64	58.7
08.00	1.00	20.3	18.4	83.4	39.5	26.0	33.8	35.9	33.6	25.0	49.5	36.3	67.6	25.0	0.88	80.7
08.15	1.25	20.2	18.3	83.4	40.0	26.2	33.1	36.5	34.1	25.2	48.4	36.9	68.3	25.2	1.22	111.8
08.30	1.50	20.3	18.4	83.4	40.5	26.4	32.5	37.0	34.7	25.4	47.0	37.4	69.2	25.0	1.67	153.1
08.45	1.75	20.4	18.4	82.6	40.8	26.6	32.5	37.5	35.1	25.6	46.4	37.8	69.9	24.5	1.40	128.4
09.00	2.00	20.4	18.5	83.4	41.2	26.8	32.1	38.0	35.6	25.8	45.5	38.3	70.7	24.6	2.98	273.2
09.15	2.25	21.0	18.8	81.2	41.9	27.1	31.4	38.7	36.3	26.1	44.3	39.0	71.5	25.4	3.30	302.5
09.30	2.50	21.0	18.8	81.2	42.2	27.3	30.6	39.2	36.8	26.3	43.4	39.4	72.3	25.3	4.74	434.6
09.45	2.75	21.5	19.1	79.8	43.0	27.6	30.4	40.0	37.5	26.6	42.3	40.2	73.1	25.3	4.07	373.1
10.00	3.00	21.7	19.1	78.3	43.5	27.7	29.5	40.6	38.0	26.7	41.0	40.7	73.8	25.8	4.85	444.6
10.15	3.25	21.1	18.8	80.4	43.8	27.8	29.1	41.0	38.4	26.8	40.2	41.1	74.5	25.5	4.31	395.1
10.30	3.50	22.1	19.2	76.2	44.3	28.0	28.6	41.6	39.0	27.1	39.5	41.7	75.0	25.7	3.98	364.9
10.45	3.75	22.4	19.4	75.6	44.9	28.4	28.5	42.3	39.6	27.5	39.2	42.3	75.7	25.8	4.57	419.0
11.00	4.00	23.0	19.8	74.4	45.5	28.7	28.1	42.9	40.4	27.7	37.6	42.9	76.2	25.7	6.08	557.4
11.15	4.25	23.2	19.7	72.3	45.8	28.8	27.8	43.4	40.9	27.8	36.5	43.3	76.7	26.4	6.13	562.0
11.30	4.50	23.2	19.7	72.3	46.2	28.9	27.3	44.0	41.5	27.9	35.2	43.9	77.2	26.9	9.07	831.5
11.45	4.75	24.2	20.1	68.6	46.7	29.2	27.1	44.7	42.3	28.2	34.1	44.6	77.7	27.4	11.22	1028.6
12.00	5.00	23.8	19.8	68.3	46.9	29.2	26.7	45.1	42.8	28.3	33.2	44.9	78.2	27.4	10.38	951.6
12.15	5.25	24.1	20.0	68.5	47.3	29.4	26.5	45.6	43.4	28.4	32.0	45.4	78.7	27.5	7.11	651.8
12.30	5.50	24.6	20.3	67.5	48.0	29.7	25.9	46.4	44.2	28.7	31.1	46.2	79.1	27.8	7.48	685.8
12.45	5.75	25.4	20.4	63.3	48.4	29.9	25.7	46.9	45.0	29.0	30.2	46.8	79.6	28.1	9.23	846.2

Table F-12 Performance data during optimization test with dryer loaded with 15kg of tomatoes, run 13, Date 30-05-09 continued

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**		**Solar radiation**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/m^2**
13.15	6.25	25.1	19.7	60.4	48.8	29.7	24.4	47.7	46.0	28.8	27.4	48.5	80.5	28.2	9.05	829.7
13.30	6.50	25.3	19.3	56.7	49.1	29.6	23.6	48.2	46.6	28.7	25.9	48.0	80.8	28.1	9.08	832.5
13.45	6.75	25.6	19.8	58.2	49.5	30.0	23.9	48.7	47.3	29.1	25.6	48.5	81.2	28.5	9.04	828.8
14.00	7.00	25.8	19.9	57.8	49.8	30.0	23.4	49.1	47.9	29.3	25.0	48.9	81.6	28.6	5.10	467.6
14.15	7.25	25.6	19.7	57.6	50.0	30.1	23.3	49.5	48.4	29.4	24.4	49.3	81.9	28.6	8.48	777.4
14.30	7.50	26.0	20.1	57.9	49.1	29.9	24.4	48.8	48.0	29.3	24.8	48.6	78.6	28.6	8.05	738.0
14.45	7.75	25.9	19.8	56.6	46.9	29.0	26.1	46.8	46.3	28.5	25.9	46.7	73.6	28.5	7.50	687.6
15.00	8.00	25.7	19.9	58.3	45.2	28.3	27.6	45.4	45.0	28.0	27.1	45.2	70.1	28.2	7.03	644.5
15.15	8.25	25.9	19.9	57.2	43.6	27.7	29.3	43.8	43.6	27.5	28.6	43.6	66.4	28.2	6.93	635.3
15.30	8.50	25.7	19.9	58.3	42.2	27.0	30.3	42.4	42.4	26.8	29.2	42.3	63.4	28.1	6.56	601.4
15.45	8.75	25.9	19.6	55.3	40.7	26.2	31.3	40.9	41.0	26.1	30.2	40.9	60.3	27.7	5.89	540.0
16.00	9.00	25.6	19.3	55.0	39.4	25.6	31.8	39.6	39.8	25.5	31.2	39.6	57.9	27.6	2.66	243.9
16.15	9.25	25.7	19.3	54.5	38.3	25.2	34.1	38.7	38.7	25.1	32.6	38.6	55.3	27.6	4.89	448.3
16.30	9.50	25.3	19.1	55.4	37.1	24.5	34.9	37.4	37.6	24.5	33.5	37.4	53.1	27.5	3.92	359.4
16.45	9.75	25.5	19.5	56.9	36.2	24.3	36.9	36.5	36.8	24.3	35.0	36.5	51.0	27.1	3.47	318.1
17.00	10.00	25.5	19.6	57.5	35.4	24.0	38.2	35.6	35.9	24.0	36.6	35.7	49.1	27.1	2.79	255.8
17.15	10.25	25.1	19.5	59.1	34.5	23.6	39.5	34.7	35.0	23.6	37.8	35.0	47.4	26.7	2.15	197.1
17.30	10.50	24.7	19.1	58.7	33.6	23.0	40.0	33.8	34.2	23.1	38.3	33.9	45.8	26.3	1.58	144.9
17.45	10.75	24.5	19.1	59.9	32.7	22.6	41.4	33.0	33.3	22.6	39.2	33.3	44.3	26.2	0.48	44.0
18.00	11.00	23.9	18.8	61.4	31.8	22.2	42.9	32.1	32.4	22.3	41.1	32.1	42.9	25.6	0.29	26.6
18.15	11.25	23.5	18.8	63.8	31.0	22.0	45.1	31.3	31.6	22.1	43.2	31.3	41.6	25.3	0.12	11.0
18.30	11.50	23.2	18.6	64.3	30.3	21.7	46.4	30.5	30.9	21.8	44.4	30.5	40.3	25.1	0.01	0.9
Average		**23.5**	**19.3**	**68.2**	**42.0**	**26.9**	**31.3**	**40.5**	**39.1**	**26.2**	**37.0**	**40.6**	**67.5**	**26.6**	**4.7**	**434.3**

Table F-13 Performance data during optimization test with dryer loaded with 15kg of tomatoes, run 14, Date 04-06-09

Time		**Ambient conditions**			**Dryer inlet conditions**			**Dryer Centre Temp (°C)**	**Dryer exit conditions**			**Dryer Average Temp (°C)**	**Storage system Temperatures (°C)**		**Solar radiation**	
Local	**Hrs**	**DB (°C)**	**WB (°C)**	**RH (%)**	**DB (°C)**	**WB (°C)**	**RH (%)**		**DB (°C)**	**WB (°C)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/m^2**
07.00	0.00	21.4	18.8	78.2	35.6	24.3	40.2	30.2	29.1	21.6	51.2	31.6	59.9	26.2	0.25	22.9
07.15	0.25	20.9	18.2	77.1	36.9	25.3	38.8	33.0	31.0	22.9	49.7	33.6	62.1	26.2	0.39	35.8
07.30	0.50	20.9	18.1	76.3	37.8	25.4	38.4	34.2	32.0	23.6	49.1	34.7	63.4	26.4	0.49	44.9
07.45	0.75	21.4	18.0	71.9	38.6	26.3	37.5	35.0	32.9	23.9	46.9	35.5	64.7	26.6	0.64	58.7
08.00	1.00	21.9	18.4	71.4	39.4	26.7	36.7	35.9	33.6	24.2	45.6	36.3	66.0	27.0	2.58	236.5
08.15	1.25	22.3	18.6	70.2	40.2	26.9	35.2	36.8	34.5	24.7	44.5	37.2	67.0	27.1	3.04	278.7
08.30	1.50	22.5	18.8	70.3	41.2	27.5	34.6	37.7	35.3	25.1	43.4	38.1	68.1	27.5	3.55	325.5
08.45	1.75	22.8	18.9	69.1	41.7	27.6	33.6	38.4	35.9	25.3	42.2	38.7	69.2	27.6	4.09	375.0
09.00	2.00	23.1	19.1	68.5	42.3	27.7	32.4	39.1	36.8	25.6	40.4	39.4	70.1	27.8	4.60	421.7
09.15	2.25	23.4	19.3	68.0	43.0	28.0	31.7	39.8	37.4	26.0	40.1	40.1	71.1	28.1	5.17	474.0
09.30	2.50	23.6	19.4	67.5	43.5	28.3	31.4	40.4	38.1	26.2	38.7	40.7	72.0	28.1	5.70	522.6
09.45	2.75	23.7	19.1	64.7	44.3	28.7	30.8	41.2	38.7	26.4	37.6	41.4	73.0	28.5	6.29	576.7
10.00	3.00	23.4	18.9	59.6	45.1	29.1	30.3	42.0	39.7	26.7	35.8	42.3	74.0	28.3	6.73	617.0
10.15	3.25	23.6	19.0	64.6	45.2	29.1	30.0	42.6	40.0	26.9	35.7	42.6	74.8	29.3	7.52	689.4
10.30	3.50	24.3	19.6	64.5	45.9	29.3	29.1	43.1	40.7	27.1	34.5	43.2	75.6	29.6	6.79	622.5
10.45	3.75	24.6	19.8	64.0	46.3	29.5	28.8	43.7	41.2	27.4	34.2	43.7	76.3	29.6	7.83	717.9
11.00	4.00	24.7	19.4	60.7	46.8	29.7	28.3	44.2	41.9	27.5	32.7	44.3	77.0	30.1	8.50	779.3
11.15	4.25	25.6	20.5	62.8	47.4	29.8	27.4	45.0	42.7	28.1	32.8	45.0	77.6	30.3	2.72	249.4
11.30	4.50	25.9	20.6	61.7	48.1	30.0	26.6	45.8	43.5	28.2	31.1	45.8	78.2	30.2	8.83	809.5
11.45	4.75	25.7	20.2	60.3	48.3	30.0	26.2	46.2	44.1	28.3	30.0	46.2	78.9	30.1	8.57	785.7
12.00	5.00	26.7	20.2	54.8	48.9	30.1	25.3	46.9	44.8	28.5	29.1	46.9	79.5	30.3	8.99	824.2
12.15	5.25	26.5	20.2	55.9	49.4	30.3	24.9	47.5	45.4	28.7	28.4	47.5	80.1	30.6	9.19	842.5
12.30	5.50	25.4	19.3	56.1	49.1	29.7	23.9	47.5	45.6	28.5	27.3	47.4	80.8	30.2	9.19	842.5

Table F-13 Performance data during optimization test with dryer loaded with 15kg of tomatoes, Run 14 Date 04-06-2009 continued

Time		Ambient conditions			Dryer inlet conditions			Dryer Centre Temp (ºC)	Dryer exit conditions			Dryer Average Temp (ºC)	Storage system Temperatures (ºC)		Solar radiation	
Local	**Hrs**	**DB (ºC)**	**WB (ºC)**	**RH (%)**	**DB (ºC)**	**WB (ºC)**	**RH (%)**		**DB (ºC)**	**WB (ºC)**	**RH (%)**		**Boiler water**	**Boiler outer surface**	**MV**	**W/m^2**
12.45	5.75	27.0	20.5	55.1	50.5	30.1	22.5	48.8	46.7	29.1	26.8	48.7	81.2	30.7	9.06	830.6
13.00	6.00	27.0	20.7	56.3	50.9	30.3	22.3	49.5	47.5	29.3	25.8	49.3	81.8	31.1	9.05	829.7
13.15	6.25	26.8	19.8	51.9	51.1	30.3	22.0	49.8	48.0	29.2	24.6	49.6	82.4	30.9	9.13	837.0
13.30	6.50	27.0	20.1	52.7	51.5	30.6	21.6	50.4	48.7	29.5	24.1	50.2	82.7	31.4	8.92	817.8
13.45	6.75	27.7	20.6	52.2	52.2	30.7	21.2	51.1	49.5	29.9	23.7	50.9	83.3	31.9	8.75	802.2
14.00	7.00	27.1	19.7	49.8	52.1	30.6	21.1	51.3	50.0	29.7	22.2	51.1	83.9	31.7	8.87	813.2
14.15	7.25	27.9	20.6	51.2	52.8	30.8	20.5	52.0	50.8	30.3	22.5	51.9	84.4	32.2	9.25	848.0
14.30	7.50	27.8	20.7	52.3	53.2	30.9	20.1	52.6	51.5	30.5	21.8	52.4	84.9	32.5	8.38	768.3
14.45	7.75	27.7	20.5	51.6	53.4	31.0	20.1	52.9	52.0	30.7	21.5	52.7	85.4	32.5	2.05	187.9
15.00	8.00	28.1	20.5	49.7	52.6	30.8	20.8	52.4	51.8	30.6	21.6	52.2	82.7	32.8	8.68	795.8
15.15	8.25	27.6	20.7	53.3	50.1	30.0	22.9	50.2	49.8	29.9	23.2	50.0	77.3	32.8	7.30	669.3
15.30	8.50	28.4	20.6	48.9	48.9	29.4	23.5	48.9	48.8	29.5	23.9	48.9	73.8	32.6	2.33	213.6
15.45	8.75	27.9	20.7	51.8	46.8	28.3	24.4	47.0	47.1	28.7	24.9	47.0	70.1	32.1	2.08	190.7
16.00	9.00	27.6	20.6	52.7	45.5	27.8	25.5	45.7	45.8	28.2	26.0	45.7	67.0	32.0	5.82	533.6
16.15	9.25	27.3	20.4	53.0	43.8	27.0	26.6	44.1	44.3	27.5	27.1	44.1	63.9	31.3	4.67	428.1
16.30	9.50	27.8	20.5	51.1	42.7	26.5	27.5	42.9	43.2	27.0	28.0	42.9	61.4	31.3	4.67	428.1
16.45	9.75	27.4	20.3	51.9	41.4	25.9	28.5	41.7	42.0	26.5	29.1	42.0	58.8	30.9	3.64	333.7
17.00	10.00	27.9	20.5	50.7	40.5	25.4	29.0	40.8	41.1	26.2	30.3	40.8	56.6	30.8	3.78	346.6
17.15	10.25	27.3	20.3	52.4	39.3	24.6	29.2	39.6	39.9	25.2	29.8	39.6	54.5	30.5	0.91	83.4
17.30	10.50	27.3	20.4	53.0	38.3	24.0	29.7	38.6	38.9	24.7	30.6	38.6	52.6	30.1	0.75	68.8
17.45	10.75	26.8	20.3	54.9	37.3	23.6	30.8	37.6	38.0	24.4	31.9	37.6	50.8	29.7	0.49	44.9
18.00	11.00	25.6	19.6	56.9	36.0	23.1	32.6	36.3	36.7	23.9	33.7	36.3	49.0	29.0	0.33	30.3
18.15	11.25	25.5	19.6	55.3	35.2	23.0	34.6	35.5	35.9	23.5	35.8	35.5	47.5	28.6	0.15	13.8
18.30	11.50	25.2	19.9	61.1	34.2	22.5	35.7	34.5	34.9	23.3	36.9	34.5	46.0	28.1	0.01	0.90
Average		**25.5**	**19.8**	**59.3**	**44.8**	**28.0**	**28.4**	**43.2**	**41.9**	**27.0**	**32.4**	**43.3**	**70.7**	**29.9**	**5.1**	**469.6**