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A Mixed Mode Low Profile Solar Tunnel Dryer for *Canarium Indicum* Nuts

T. Curtis[1], R. Corkish[1*], R.J. Fuller[2] and A.B. Sproul[1]
[1]*School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney NSW 2052*
[2] *School of Architecture and Built Environment, Deakin University, Geelong Victoria 3217*

*E-mail: *Corresponding author: r.corkish@unsw.edu.au*
Phone: +61 2 938 54068

Abstract

Canarium indicum nuts are dried and consumed widely across the Pacific Region. Traditional methods of drying offer little process control resulting in highly variable product quality and loss. A more reliable and effective drying technology is required but the technology must suit local conditions. This paper describes a low profile solar tunnel dryer designed for batch drying of small quantities of the nuts. Prototypes have been tested. Experimental results indicate that drying temperatures are within the range to achieve good kernel quality and that the desired final moisture content for safe storage could be achieved after 30 hours of exposure.

1. Introduction

The *Canarium indicum* nut is an important resource to the indigenous peoples of Melanesia. The nut is high in nutritional content and potentially a lucrative crop for export. The nuts are enjoyed raw, dried or roasted and are often incorporated into traditional puddings mixed with available starches such as cassava and taro (Chaplin, 1988). Medicinal uses have also been explored, including using the kernel oil for arthritis treatment and prevention (Sanderson & Sherman, 2004. Unfortunately, due to their high oil content, the kernels, once harvested, can become rancid very quickly, ruining the possibility of consumption, storage, processing or export. Drying is one method to reduce the impact of this problem. Traditionally, *C. indicum* nuts are dried openly in the sun (Evans, 1991). However, this method allows very little control during the drying process and can produce considerable variation in the finished product, again limiting the possibilities for sale or export. Small electric food dryers have also been used but in most of the areas where the nuts grow these dryers rely on imported diesel for electricity generation and are therefore expensive to operate. The problem is therefore to find a suitable dryer which is affordable, easy to operate and that can be constructed mainly from local materials. This paper describes the development, testing and performance of a locally-constructed solar tunnel dryer suitable for the preservation of *C. indicum* nuts in Vanuatu. Initially, the paper presents a description of the nuts and their processing requirements. The local climate in Vanuatu where the dryer will be used is also summarized. The solar dryer developed to address the problem outlined above is then described. Modeling and field testing results are presented and discussed, followed by some concluding remarks.

2. *Canarium Indicum* Nuts

Canarium indicum is the preferred scientific name for a nut from the Burseraceae or torchwood family, having several common names: galip in Papua New Guinea, nangai in Vanuatu and ngali in the Solomon Islands (Thomson & Evans, 2006). There are approximately 75 species belonging to the same genus which is found mainly in the Pacific Island regions and tropical Asia (Leenhouts 1959), as cited in (Nevenimo, 2007). Typically, the *C. indicum* trees are found in subtropical and cool tropical regions having an annual average temperature range of 18° to 24°C, according to (Janick & Paull 2006), and 24° to 27°C according to Duke (1989) and a high annual rainfall of 1500-2500 mm is also reported where the C. indicum trees grow (Janick & Paull, 2006). The species thrive in humid wetlands and although often planted at higher altitudes, *C. indicum* will rarely be found to grow naturally above 250 m (Duke 1989). The phenology is determined by day length, with fruits maturing in West New Britain, PNG (7°S) as early as May but as late as October or November further from the equator in central Vanuatu (17°S) (Evans, 1994; Bourke et al., 2004). The nuts can be harvested all year-round in Santa Cruz, Solomon Islands (9°S), although the crops tend to be small (Duke, 1989). In favorable conditions, the *C. indicum* trees can start flowering 5-7 years after planting (Thomson & Evans, 2006). The fruits, 60 x 30 mm, start out green in color and can take 5-8 months before turning dark purple; signaling maturity (Leenhouts, 1959). The kernel is reported to be approximately one sixth of the total nut mass (Carlos & Dawes, 1990), yielding a mean kernel mass ranging from 1.38 to 3.65g (Nevenimo et al. 2007).The size of the nut in shell can vary considerably by region but for example, in Vanuatu samples measured between 36-56 mm long by 23-34 mm wide and had a fresh weight of 9-18 g (Thompson & Evans, 2006). The output of nuts per tree is also quite variable, measured at between 13 and 220 nuts per tree (Nevenimo et al., 2007). There is some variation in the reported values of the composition of the C. indicum kernels and values for selected properties from the literature are shown in Table 1.

Table 1: Selected properties of raw C. *indicum* kernels

Properties	Maima (no date)	English & Aalbersberg (1996)	Evans (1991)
Moisture (%)	24	35.4	-
Oil/fat (%)	-	45.9	74.9
Protein (%)	-	8.2	14.2

Due to the high oil content, *C. indicum* kernels are vulnerable to rancidity, making processing quite challenging. Limited trials have been documented and a traditional process has been documented. Firstly, the mesocarp (fleshy outer layer) must be removed by one of the known methods including bruising the fruit using stones, leaving bags of the fruits to ferment in sea water or submerging the fruits in boiling water for several minutes (Carlos & Dawes, 1990; Evans, 1991). Traditionally, the nuts are then dried in their shells naturally in the sun or over a fire (Evans, 1991). However, these drying methods allow very little control over the product quality. Evans (1994) suggests oven drying kernels at 60°C for ten hours results in desirable product quality for consumer acceptance and long shelf life. On the other hand, it is suggested that drying the kernels still attached to the testa (thin paper-like layer covering the kernel) at 55°C for eight hours, resulted in a suitable product (Maima, no date). More recent work

(Wallace et al., 2012) found that drying the nuts-in-shell at a constant temperature of 60˚C resulted in significant browning of the kernel but drying trials at temperatures of below 40˚C resulted in higher over-all kernel quality with no notable discolouration. For best shelf storage, it is recommended that the kernel moisture be reduced to 1.5-2.0% (Evans, 1994) or at most 2.8% for vacuum packaging (Maima, no date). However, once the kernels have been removed from their shells, the shelf-life is decreased and thus it is preferable to store kernels in their shells (Nevenimo et al., 2007). Factors affecting the quality of the stored nuts include: how mature they were when harvested, storage conditions and the amount of moisture retained (Nevenimo et al., 2007). Wallace et al., (2012) found that nut-in-shell samples dried to a moisture content of 6% (3.5% kernel equivalent) showed no signs of visible deterioration after six months when vacuum packed kernels were stored at 30˚C and nine months at 25˚C. Nut-in-shell samples dried to 7% moisture content were found to retain their quality after eleven months of storage in low humidity conditions.

3. Climatic Conditions

Figure 1 indicates that the solar radiation data for Port Vila, the capital of Vanuatu (17°45'S 168°18'E), has an average of 5.65 – 6.67 kWh/day (peak sun hours) from September to November, which is the typical harvest season for this crop (Bourke et al., 2004). Figure 2 shows the monthly rainfall for Port Vila, indicating that the hot wet season is from November to April and the cooler dry season is from May to October. The average temperature and relative humidity at this location from September to November are 26°C and 82% respectively (NASA, 2007). The peak harvest season for Vanuatu is in September, highlighted in Figure 1 and Figure 2.

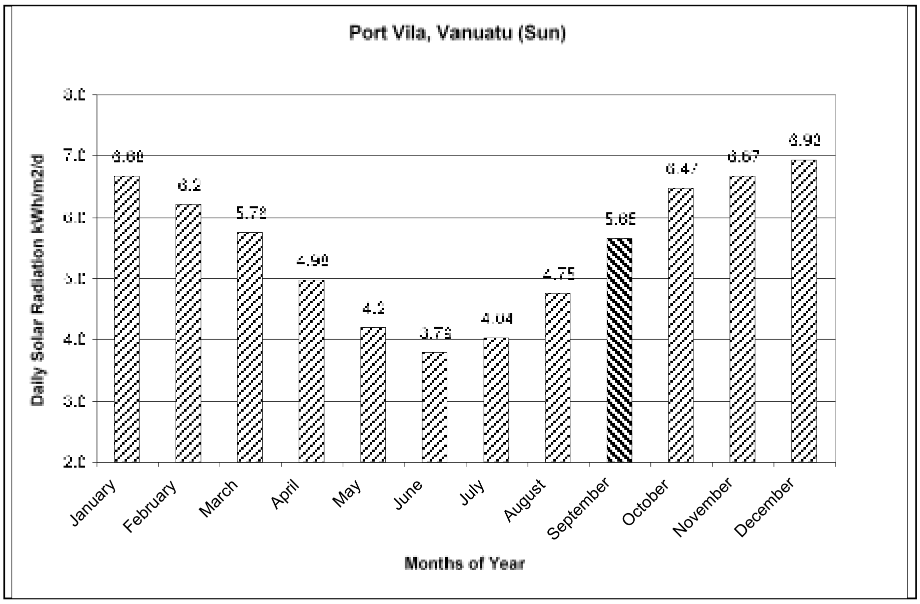

Figure 1: Monthly average global horizontal solar radiation for Port Vila, Vanuatu

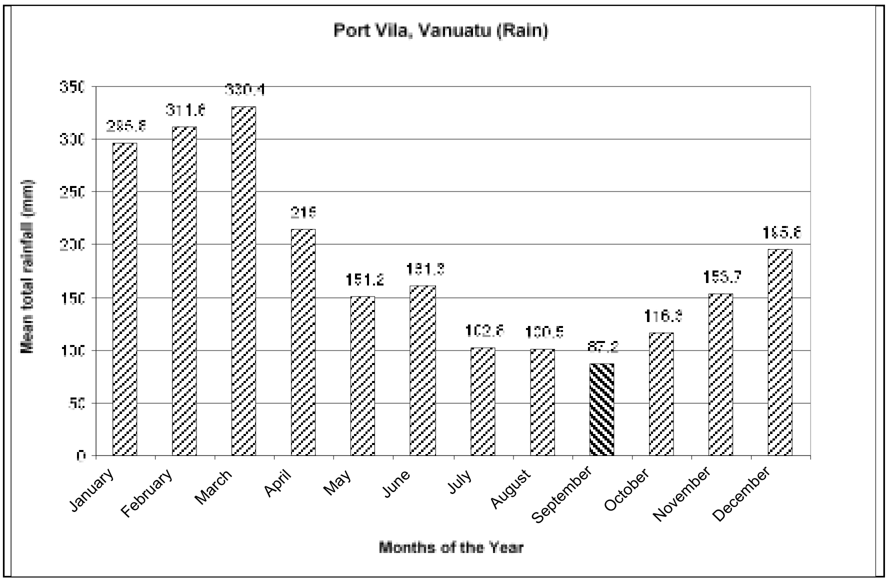

Figure 1: Monthly average rainfall data for Port Vila, Vanuatu

4. Solar Tunnel Drier

A low-profile solar tunnel dryer was selected as the most appropriate technology for the small-scale drying of the *C. indicum* nuts in Vanuatu. Selection was based on a number of criteria: ease of operation and construction, maximum use of local materials, cost and drying efficacy. Although some imported materials and components are used in its construction, the dryer is simple and will be inexpensive to operate. Figure 3 shows the unit in a) open and b) closed positions. Prototypes of the solar dryer were constructed in Sydney, Australia, and in Port Vila, Vanuatu. The dimensions of the dryers are shown in Table 2. Half of the length of each unit acts as a pre-heater and the other half as the drying zone where the crop is placed. The dryer base is constructed from timber and is topped with approximately 40 cm of insulation, which in turn is covered with a 4 mm thick black-painted timber layer. Three 20 mm thick timber beams along half the length of the unit support a black-painted corrugated iron absorber sheet. Together the black-painted timber layer and corrugated iron form the 0.04 m deep lower channel. The hinged tunnel top assembly is constructed from bent bamboo and UV stabilised polyethylene film. Adhesive foam strips ensure a good seal to prevent air leakage. Two PV-powered DC fans mounted at the pre-heater end force ambient air through the dryer.

(a) (b)

Figure 3 Solar tunnel dryer in open (a) and closed (b) positions.

Table 2: Key dimensions of the two solar tunnel dryer prototypes

Dimensions	**Sydney**	**Vanuatu**
Total dryer length	3 m	2.4 m
Dryer width	1 m	1.2 m
Depth of base	0.1 m	0.1 m
Tunnel top height	0.4 m	0.4 m
Length of pre-heater	1.5 m	1.2 m
Length of dryer area	1.5 m	1.2 m
Lower channel depth	~ 0.04 m	~ 0.04 m

5. Modelling Approach

The use of equivalent electronic circuits to model thermal processes has been documented (Cengel & Turner, 2005; Cengel, 2007; Sproul et al., 2012). The roots of this analogy can be traced as far back as Georg Ohm (Archibald, 1988). Initially, an equivalent electric circuit model of a solar tunnel dryer where the air is assumed to flow through the single air channel created by the top of the absorber plate and the polyethylene cover was developed (Figure 4). A series-parallel arrangement is used to simulate the thermal energy gains and losses of the solar dryer. The equivalent electric circuit, together with resistor and capacitor values, for this single-channel solar tunnel dryer is shown in Figure 5 and Table 3 lists the electrical components in the circuit and briefly describes the corresponding role they play in modeling the thermal performance of a solar tunnel dryer. The thermal resistances are constant along the length of the dryer and have units of m^2KW^{-1}. Time in the electrical analogy corresponds to distance along the dryer. Justification of the model is found in Sproul et al. (2012).

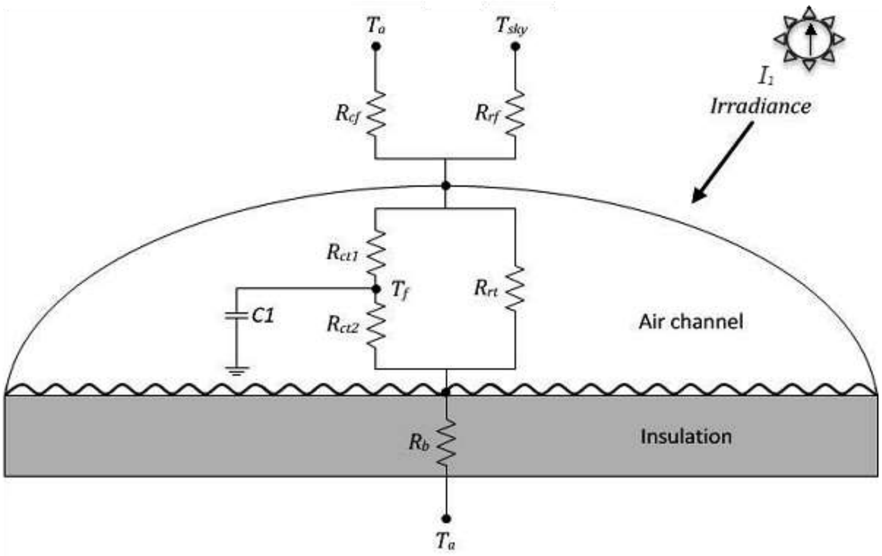

Figure 4: Cross-sectional view of the solar dryer showing electrical components

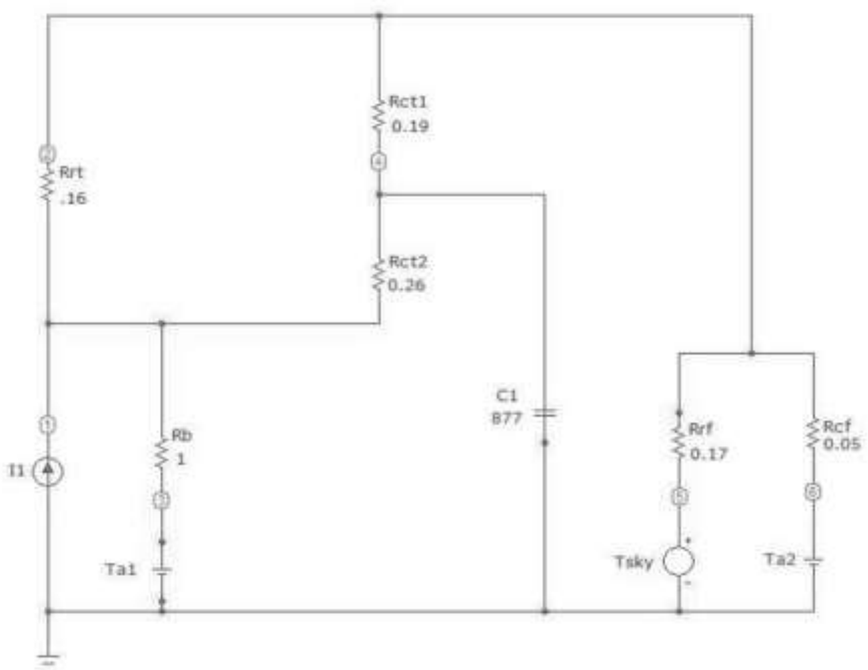

Figure 5: Equivalent electric circuit for the single-channel solar tunnel dryer

Table 3: Circuit components and their description for the single-channel solar dryer model

Electrical Component	Analagous Thermal Component
Current source (I_1)	Absorbed fraction of incident irradiance.
Resistor (R_{rt})	Resistance to radiative heat transfer between absorber

	and cover.
Resistors (R_{ct1})	Resistance to convective heat transfer between cover and air within dryer.
Resistor (R_{ct2})	Resistance to convective heat transfer between absorber and air within dryer.
Resistor (R_b)	Resistance to conductive heat transfer through the bottom surface.
Resistor (R_{rf})	Resistance to radiative heat transfer between cover and sky.
Resistor (R_{cf})	Resistance to convective heat transfer between cover and ambient air.
Voltage source (T_{sky})	Sky temperature.
Capacitor (C_1)	Capacitance of air within dryer.
Batteries (T_{a1}, T_{a2})	Ambient air temperature.

The current source (I_1) acts as the irradiance input in the circuit and has units Wm^{-2}, and the ambient temperature is represented with batteries (T_{a1}, T_{a2}). The capacitor (C_1) represents the thermal capacitance of the volume of air moving through the dryer. The sky's radiative temperature is represented in the circuit by a stepped voltage source component (T_{sky}). This works by starting the simulation at the ambient temperature, then stepping at $t = 0$ to the sky temperature, which models the air entering the dryer at ambient temperature, since time in the electrical model represents position in the thermal model (Sproul et al., 2012). The purpose of this single-channel model was to validate the electric circuit analogy approach. Figure 6 shows the output of the single-channel model compared to published results (Garg & Kumar, 2000). The predicted temperatures compare relatively well, especially in the middle of the day. The model is more affected by lower irradiance levels, heating up less quickly and cooling down more rapidly. The overall agreement achieved was considered good enough to proceed with this modelling approach.

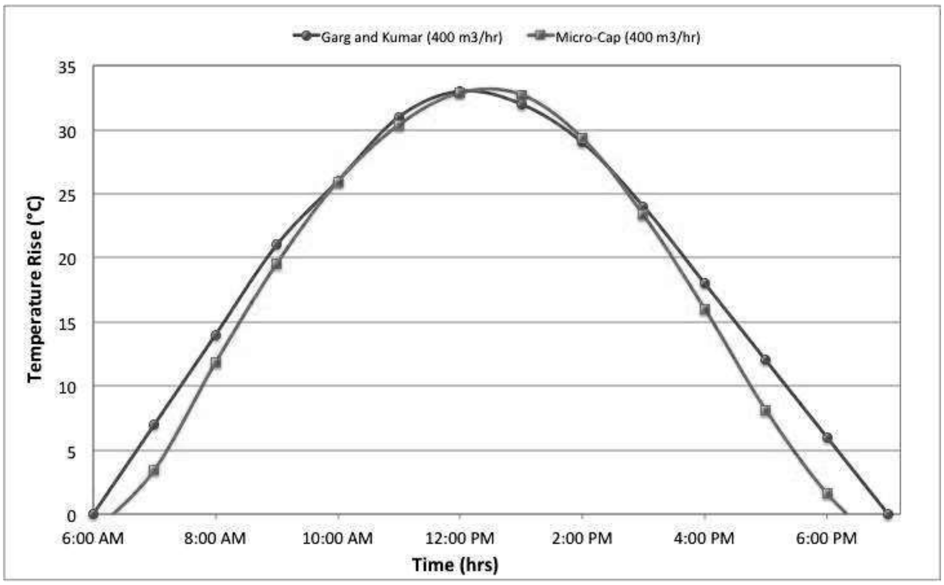

Figure 6 Comparison of model of single-channel solar dryer with results of [21]

Previous tunnel dryers, such as that developed by at the University of Hohenheim (Innotech, 2014) in Germany, have been considerably longer (20 m) and this has meant that a single channel has been able to generate the temperature levels generally required for drying. The current solar tunnel dryer is much shorter and therefore to compensate for this and reduce the convective heat losses a double-channel system was developed. In this system, all the incoming air passes through a channel between the underside of the absorber plate and the top of the insulation cover (Figure 7). The prototypes built in both Sydney and Vanuatu incorporated this dual channel approach. The equivalent electric circuit single-channel model was adapted by adding a second capacitor (C_2) to represent the air below the absorber and an additional three-resistor network to represent the radiative and convective heat transfers in the lower channel. The circuit, together with resistor and capacitor values, is shown in Figure 8. The results for all subsequent modeling and experimental testing of the dual-channel solar tunnel dryer are presented below.

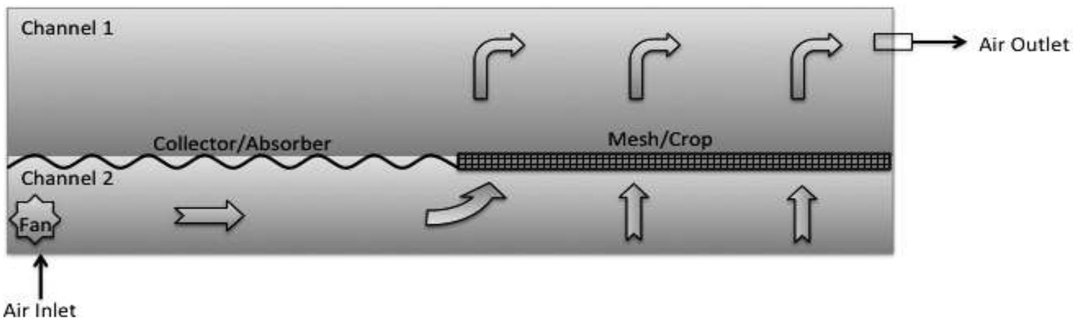

Figure 7 Schematic diagram of airflow path in dual-channel solar tunnel dryer

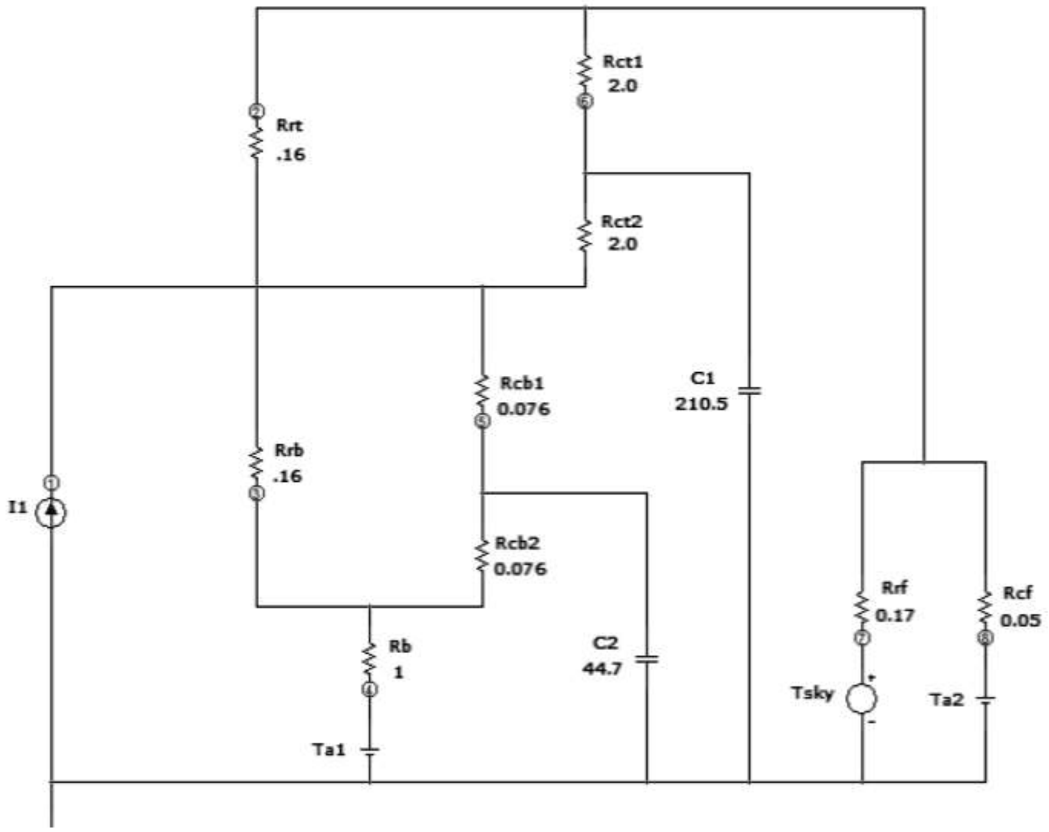

Figure 8: Equivalent electric circuit for the dual-channel solar tunnel dryer

Table 4: Description of additional components used in the dual-channel Micro-Cap model

Additional Components	Description
Capacitor (C_1)	Capacitance of air volume above absorber.
Capacitor (C_2)	Capacitance of air volume below absorber.
Resistor (R_{rb})	Resistance to radiative heat transfer between the absorber and lower channel surface.
Resistor (R_{cb1})	Resistance to convective heat transfer from absorber to air flowing in lower channel.
Resistor (R_{cb2})	Resistance to convective heat transfer from lower channel surface to air flowing in lower channel.

6. Results and Discussion

The performance of the dryer has been evaluated in terms of both thermal performance and drying efficacy. The former allows an evaluation of how effectively solar radiation has been transformed into heat and the latter shows how well this heat has been used to dry the crop.

6.1. *Thermal Performance*

Figure 9 compares the pre-heater outlet air temperatures measured on the Sydney prototype on March 8th 2011 with predictions from the model. Irradiance on a tilted plane (33˚ N) was measured and recorded at one-minute intervals at a Sydney test site and the hourly average of these values was used in the steady-state simulation. A constant air mass flow rate of 400 m^3h^{-1} was used in the simulations. Once the solar irradiance rises to approximately 550 W/m^2, the PV-powered fans commence operation in the model. The difference between the measured and predicted values in the pre-heater outlet temperatures at the beginning of the day is due to the delay in fan initialization in the actual prototype. Without the fans running, the temperatures continue to rise in the Sydney solar dryer until approximately 9:30 am, when the fans turn on. Between 10:00 am and 2:00 pm the difference between the measured and predicted pre-heater outlet temperatures of the solar dryer remain within one degree of each other. From 3:00 pm onwards, when the irradiance level falls below 600 W/m^2, the pre-heater outlet temperature of the simulated dryer pre-heater outlet temperature also begins to decline. This is for two reasons. Firstly, the simulated solar dryer is more affected by the lower irradiance levels due to the nature of this steady-state analysis in which no account is taken of any heat stored within the dryer materials. This could be achieved with the addition of another capacitor, as used for the air within the dryer. More detailed work would be required to determine the effective value of the thermal capacitance of all the dryer materials. In view of the level of agreement achieved, this was considered to be unnecessary at this stage in the model's development. Secondly, the lower temperatures are a result of the constant airflow rate, which continually cools down the simulated dryer regardless of the irradiance levels. On the other hand, the actual solar dryer pre-heater is able to maintain a higher outlet temperature for longer because of the thermal capacity of the solar dryer and the fluctuations in irradiance regulate the output airflow from the fans proportionally. Importantly, the preheater outlet air temperatures are in the range (30-38°C) as required to achieve good kernel quality (Wallace et al. 2012).

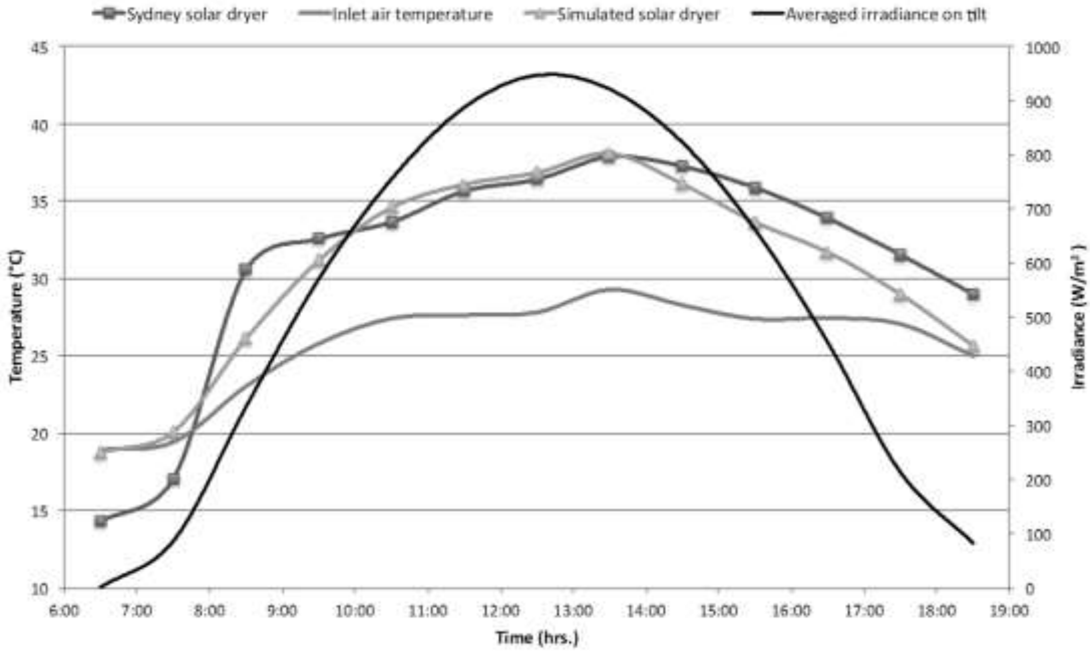

Figure 9: Pre-heater outlet air temperature comparison between constructed dual-channel model in Sydney and simulation (March 8th, 2011)

6.2. Drying Performance

Three different groups of *C. indicum* nuts (approximately 20 kg) were obtained from Papua New Guinea, each of which had been collected under different conditions. The first group, "A", consisted of nuts which had already fallen from the trees and had partially decayed naturally before collection. Group "B" consisted of nuts that had been collected directly from the trees and the outer flesh removed immediately before packaging for airfreight. Group "C" contained nuts also collected from trees directly. However, the latter trees were from a different village and environment. A fourth, much smaller group of nuts, "V" were collected from Vanuatu, but the collection method is unknown. These four groups of nuts were kept frozen prior to testing and were monitored independently during the solar drying to observe the effects that may have resulted from the collection method. Table 4 shows the final moisture content for samples of nuts from Groups B and C determined after thirty hours of exposure in the solar tunnel dryer. There are several missing values from all of the sample groups e.g. B1 and B3, since when these samples were opened, the kernel exhibited decay or other signs of poor quality, rendering the samples unusable. The remaining samples indicated that drying to the required final moisture content could be reliably achieved in the solar tunnel dryer.

7. Implementation

The two experimental dryers that were constructed in Port Vila were demonstrated and promoted to parliamentarians and other interested people in December 2010 at a local business, The Kava Store, and were subsequently used by the business for preserving a wide variety of locally produced foods and kava. The proprietor, Mr Charlot Longwah, used them there as production tools in that business and, later in his new business, South Pacific Nuts, strongly promoted their widespread adoption throughout Vanuatu and elsewhere in Melanesia and also argued publicly for value adding and export of produce.(Longwah, 2012; Vanuatu Daily Post, 2013; Binihi, 2013). Further, he conducted training courses on solar nut drying (Vanuatu Daily Post, 2014; Longwah, 2013).

Table 4: Final moisture content (% wb) from sample groups B and C

Sample Group (B)	Final moisture content (% wb)	Sample Group (C)	Final moisture content (% wb)
B2	3.2	C1	3.2
B4	3.1	C2	2.8
B5	2.8	C3	3.0
B6	3.9	C5	2.6
B7	3.1	C6	3.0
B8	2.5	C8	2.8
B9	3.1	C9	4.5
B10	3.0	C10	2.9
Average	3.1	Average	3.1

8. Conclusions

The aim of the research described in this paper has been to develop an effective solar dryer capable of drying *C. indicum* nuts in Vanuatu. The focus of the design was on sustainability and maximizing the use of locally-available materials in manufacture. The solar dryer developed proved easy to use, uses only solar energy for its operation and is capable of producing a commercial grade dried product. An electric circuit technique was used to develop a theoretical model of the solar dryer. A comparison of simulated and measured pre-heater outlet temperatures from a physical prototype of the solar dryer built and tested in Sydney shows that the technique can be used successfully to predict the performance of the pre-heater using real weather data inputs. This is a useful modeling tool that can now be confidently used for further analysis in similar solar dryer design. Possible dryer adaptations include lengthening or shortening the pre-heater in order to achieve either higher or lower temperatures, depending on the requirements of the product to be dried. Solar drying tests were conducted and demonstrated that the prototype dryer operated within the design temperature range of 50-60˚C and *C. indicum* kernel samples could be dried to a final moisture content of 2.5-3.5 (% wb) and a final nut-in-shell moisture content between 5–6.5% (% wb). The testing of the solar dryer conducted in Vanuatu proved that the concept and design was a feasible solution to meet the needs of the local people to dry *C. indicum* nuts. Further longer term testing in Vanuatu is required because the time frame for the dryer construction in Vanuatu did not align with the seasonality of the *C. indicum* nuts. In addition, some extreme weather did not allow for further testing at the time of the site visit.

References

Archibald, T. (1988). Tension and potential from Ohm to Kirchhoff, Centaurus 31, 2, 141-163.

Binihi, R. (2013)., Nangai could make ni-Vanuatu millionaires says Longwah, Vanuatu Daily Post, 24 January.

Bourke, R., Camarotto, C., et al. (2004). Production Patterns of 180 Economic Crops in Papua New Guinea, Coombs Academic Publishing, Research School of Pacific and Asian Studies, ANU, Canberra ACT 0200.

Carlos, J. and S. Dawes (1990). South Pacific tropical nut cultivation: status and outlook. Institute of Research Extension and Training, University of the South Pacific, Apia, Western Samoa.

Cengel, Y. and R. Turner (2005). Fundamentals of Thermal-Fluid Sciences, McGraw-Hill.

Cengel, Y. A. (2007). Heat and mass transfer : a practical approach Boston : McGraw-Hill.

Chaplin, G. E. (1988). The status of *Canarium indicum* in Solomon Islands—an appropriate species for small-scale community forestry. Forest Research Note. FRO No. 50-18/88. Solomon Islands Forestry Division,: 31 pp.

Duke, J., A., (1989). Handbook of Nuts. CRC Handbook of Nuts. Boca Ratan, Florida USA, CRC Press, Inc.

English, R. and Aalbersberg, W. (1996). Pacific Islands Foods: Description and nutrient composition of 78 local foods, Institute of Applied Sciences, University of the South Pacific; Australian Centre for International Agriculture Research; Australian Government Analytical Laboratories. IAS Technical Report 96/02: 94 pp.

Evans, B. R. (1991). The production, processing and marketing of ngali nuts (*Canarium* ssp) in Solomon Islands. Honiara, Ministry of Agriculture and Lands, Dodo Creek Research Station.

Evans, B. R. (1994). Marketing galip nut (*Canarium* ssp.) in Kandrian and Gloucester Districts, West New Britain, Papua New Guinea. Kimbe, Papua New Guinea, Kandrian Gloucester Integrated Development Project (unpublished).

Garg, H. P. and Kumar, R. (2000). Studies on semi-cylindrical solar tunnel dryers: thermal performance of collector. Applied Thermal Engineering 20, 2, 115-131.

Government of Vanuatu (2007). Vanuatu Meteorological Services, Ministry of Infrastructure and Public Utilities.

Innotech (2014) Solar tunnel dryer - Hohenheim. Available at:http://www.innotech-ing.de/Innotech/english/Tunneldryer.html Accessed: 25/2/2014

Janick, J. and Paull, R., Eds. (2006). The Encyclopedia of Fruit and Nuts. Cambridge, Cambridge University Press

Leenhouts, P. W. (1959). A monograph of the genus Canarium (Burseraceae). Leiden, Ijdo.

Longwah, C. (2012). Solar crop dryer can revolutionise nangai production. Vanuatu Daily Post, 11 July.

Longwah, C. (2013). Solar food dryers, course outline and notes.

Maima, M. (unpublished). Processing of galip nut in FPPU, Food Processing and Preservation Unit, Unitech, Lae.

NASA Langly Research Center (2007). NASA Collaboration Benefits International Priorities of Energy Management (RETscreen Software), NASA.

Nevenimo, T., Moxon, J. and Wemin, J. (2007). Domestication potential and marketing of *Canarium indicum* nuts in the Pacific: 1. A literature review. Agroforestry Systems 69(2): 117-134.

Sanderson J. and Sherman B. (2004). A nut to crack a growing problem. Partners in Research for Development. Australian Centre for International Agricultural Research, Canberra, Australia.

Sproul, A.B., Bilbao, J.I. and. Bambrook S.M (2012). A novel thermal circuit analysis of solar thermal collectors. Proc. 50th Annual Conference of the Australian Solar Energy Society, Melbourne, Dec.

Thompson, L. and B. Evans (2006). *Canarium indicum* var. *indicum* and *C. harveyi* (Canarium nut).

Vanuatu Daily Post (2013). Rewriting the production of Pacific high value crops., 9 February.

Vanuatu Daily Post (2014). South Pacific Nuts to conduct free extensive training for Vanuatu farmers, 8 March.

Wallace, H., Carter, J., Austin, J., Poieneu, M., Walton, D., Randall, B. and Vijii, I. (2012). Processing of Canarium indicum nuts: adapting and refining techniques to benefit farmers in the South Pacific, Australian Centre for International Agricultural Research. (http://aciar.gov.au/publication/fr2012-12)

Acknowledgements

Mr Charlot Long Wah, then proprietor of the Kava Store in Port Vila, Vanuatu, and repository of South Pacific food preservation knowledge, is acknowledged for his guidance and help and contribution in testing the solar dryers. Until he passed away in February 2015, he was a leading advocate for growers in Vanuatu to process and add value to their products and was a pioneer in the treatment of tropical nuts and kava for export.