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Research Application Summary

Design and simulation of an integrated solar cooker -dryer system

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Abstract

Several solar drying technologies exist in Uganda, but marred with multiple deficiencies such as inefficient conversion of trapped solar radiations into thermal energy, prolonged drying times, among others. The aim of this study was to design and simulate an integrated solar cooker-dryer system with a simple biomass cooker using locally available technology and materials. The major component of this study entailed an assessment of existing solar drying technologies. Through purposive sampling, four existing dryers were assessed to gather information that guided the development of a better drying technology. The results from performance evaluation of the existing solar dryers showed a substantial drop in ascorbic acid content by about 27.9 mg/100g of pineapple (*Ananas comosus*) dried in natural convection drying and 14.5 mg/100 g during forced air drying. It showed that the natural convection solar mode of operation was slowest in drying the samples, with the solar forced air mode being fastest under the prevailing meteorological conditions (which were generally unfavorable from November through to December). The results showed a considerable advantage of forced air solar dryer over the natural convection solar dryer in terms of drying rate and reduced risk of spoilage. In view of alleviating the weather restriction experienced by farmers in crop drying especially for pineapples, it is recommended that dryers be designed with backup cooker for supplementing the solar energy and enhancing airflow to increase the drying air temperature. This results into increase in the drying rate and reduced spoilage. Using performance results as boundary conditions, the temperature distribution of the airflow inside the dryer was visualized using OpenFOAM CFD. Uniform temperature distribution was achieved as a result of forced air system and incorporation of a biomass cooker.

Key words: *Ananas comosus*, biomass cooker, postharvest handling, solar dryer, turbo-ventilators, value addition

Résumé

Plusieurs technologies de séchage solaire existent en Ouganda, mais elles présentent de multiples lacunes telles que l'inefficace conversion des rayonnements solaires piégés en énergie thermique, et des temps de séchage prolongés. Le but de cette étude était de concevoir et de simuler un système solaire cuiseur-séchoir intégré avec un simple cuiseur à biomasse, en utilisant les technologies et matériaux localement disponibles. La principale composante de cette étude a été une évaluation des technologies existantes de séchage solaire. À l'aide d'échantillonnages délibérés, quatre sécheurs existants ont été évalués afin de recueillir des informations qui guident la conception d'une meilleure technologie de séchage. Les résultats de l'évaluation de la performance des séchoirs solaires existants ont montré une baisse substantielle de la teneur en acide ascorbique d'environ 27,9 mg / 100 g d'ananas (Ananas comosus) séché par convection naturelle, et de 14,5 mg / 100 g pendant le séchage à l'air forcé. Ceci a montré que le mode opératif solaire de convection naturelle était le plus lent dans le séchage des échantillons alors que le mode solaire d'air pulsé étant le plus rapide dans les conditions météorologiques prédominantes (généralement défavorables de novembre à décembre). Les résultats ont montré un avantage considérable du sécheur solaire à air forcé sur le séchoir solaire à convection naturelle en termes de taux de séchage et de réduction du risque de détérioration. En vue d'alléger les contraintes climatiques rencontrées par les agriculteurs dans le séchage des cultures, en particulier pour les ananas, il est recommandé que les séchoirs soient conçus avec cuiseur de secours pour compléter l'énergie solaire et améliorer le flux d'air afin d'augmenter la température de l'air de séchage. Il en résulte une augmentation du taux de séchage et une réduction du niveau de détérioration. En utilisant les résultats de performance comme conditions limites, la distribution de la température du flux d'air à l'intérieur du sécheur a été visualisée à l'aide de CFD OpenFOAM. Une répartition uniforme de la température a été obtenue grâce au système d'air forcé et à l'incorporation d'un cuiseur à biomasse.

Mots-clés: Ananas comosus, cuiseur à biomasse, gestion post-récolte, séchoir solaire, turboventilateurs

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Background

Food insecurity and poor livelihoods continue to prevail partly due to high post-harvest losses, limited product diversity, low value addition, and low farm gate prices (Lipinski *et al.,* 2013). Even though a number of research and development efforts have been made to improve agricultural productivity, farmers still incur substantial post-harvest losses which translate into low incomes from their agricultural activities. Regardless of decades of educational and research efforts, the most common causes of postharvest losses in developing countries continue to be rough methods of handling and inadequate cooling and temperature maintenance.

Fruits such as mangoes (*Mangifera indica*) and pineapples (*Ananas comosus*) are produced in large quantities but the incomes derived from these products are normally low due to inappropriate postharvest handling facilities. Drying of agricultural products is still the most widespread preservation technique in Africa due to its low cost and it is becoming a better alternative to marketing fresh fruits since the demand for high quality dried fruits is steadily increasing all over the world. Several solar drying technologies exist in Uganda (Fig.1 and 2), however they are marred with multiple deficiencies such as low throughput, unpredicted drying times due to weather dependency and inherent difficulty in maintenance of hygiene. Therefore, the aim of the study was to develop an integrated solar cooker-dryer system with a simple biomass cooker using locally available materials.

In many parts of the world there is an increasing awareness that renewable energy has a vital role to play in extending technology to the farmers in developing countries to increase

Figure 1. Direct Solar Dryer models used for drying pineapple slices in Kayunga

Figure 2. Tunnel solar dryer at Makerere University

productivity (Karekezi and Waeni, 2002). In developing countries where access to power grids or reliable sources of energy is difficult, solar energy has been able to satisfactorily meet the energy needs of communities for lighting, drying of crops, water pumping etc. (Yamoah *et al.,* 2014). The current methods of solar drying however result into inferior quality products due to changing weather conditions and exposure to pests, dust, moisture and microorganisms. There is therefore need of designing better technologies to improve solar drying.

A number of efforts have been made to add value to pineapples through fruit juice processing, wine making and drying, but this has not fully addressed the challenge of huge losses at peak production times. The challenge still exists because presently, the local pineapple industry in Uganda has concentrated on the sale of fresh produce. However, for the export of fruits and vegetables, emphasis has been on the production of solar dried chips. Under this arrangement, Fruits of the Nile (FON), a private Ugandan Company was formed to assist and support individuals and groups interested in producing solar dried fruits and vegetables (Agona *et al.,* 2002). As a consequence, there has been an effort to promote use of solar dryers. Although several dryers have been designed in Africa, their adoption among rural farmers has been less successful. Unpredictable weather patterns and high product losses during drying are the two major constraints for dried fruits.

Recent studies by Fudholi *et al.* (2010) have demonstrated the possibility of using dryers which incorporate thermal storage of solar energy using rocks or water. The stored energy is later used when there is no solar radiation (at night or on cloudy days). Other studies use photovoltaic cells to power a fan which removes moist air inside the dryer. Similarly, Fudholi *et al.* (2011) and Pangavhane and Sawhney (2002) studied the possibility of hybrid dryers that complement solar energy with conventional energy sources such as biomass, electricity and LP gas. This was intended to achieve better drying process, making it continuous and even useful during nights and cloudy days where an unfinished drying process could be concluded or a new process began. Therefore, the objective of this study is to develop an integrated solar-cooker dryer system in order to reduce wastage, improve product quality and ultimately enhance income security for small-holder horticultural farmers. To evaluate and optimize the new design, high-fidelity simulations using OpenFOAM CFD were performed to accurately model the interactions especially between fluid dynamics and structural mechanics.

Study description

The study was carried out in Kigayaza village, Kangulumira sub-county of Kayunga district in Uganda. Kayunga is approximately 74 kilometers northeast of Kampala, Uganda's capital. The coordinates of the town are 0°42'12.0"N, 32°54'13.0"E (Figure. 3). The area was chosen because there were substantial numbers of pineapple growers (both certified organic and conventional type) and fruit driers (processors).

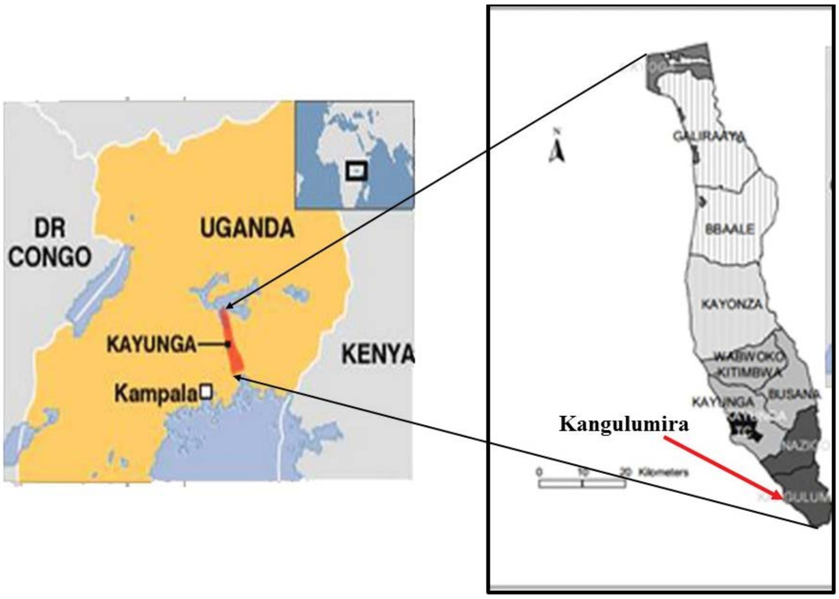


Figure 3. Kangulumira, Kayunga District, Uganda

From the baseline survey, there were 28 registered drying units with each unit having an average of 15 direct solar driers making it the sub county with most fruit driers in Uganda. The choice of the target community was based on the fact that pineapple farmers in the district are already organized in groups. The area was also selected because of the rich experience farmers therein have regarding solar fruit drying and that solar drying models developed through several research initiatives have been built and tested on the drying sites in this area.

The study focus was to design and simulate an integrated solar cooker-dryer system with a simple biomass cooker modification using locally available technology and materials. However, prior to the design and simulation of this dryer, a baseline survey was conducted during the month of June 2015 to explore the constraints faced by pineapple farmers during post-harvest management of pineapples and its impact on their income security.

Data were collected from 109 randomly sampled pineapple farmers and/or processors through key informant interviews, focus group discussions and semi-structured interviews and analysed using SPSS. This was then followed by a general assessment of the existing drying technologies in the area with a view of ascertaining their performance-related strengths and weaknesses and making recommendations for new efficient solar cooker-dryer design. Measurements of solar radiation, temperature, humidity, air speed inside the dryer and pineapple weight loss data were used to compare the effectiveness of the two dryers. Open field operation and manipulation CFD was then applied to optimize the proposed design.

Results and Discussion

The results of the performance evaluation test carried out with the solar dryers in Kangulumira show that under all-weather conditions, the solar dryer with a forced air flow system performs better than the natural convection solar dryer. Despite the fact that the dryer evaluation was carried out in November 2015 under ambient temperature of 22-35^{0}C and a higher mean relative humidity period of 68–75%, the forced air dryer attained a higher temperature range of 60-65 ^{0}C whereas the natural convection dryer attained lower temperature ranges of 46–54 ^{0}C as shown in the profile in Figures 4 and 5. The temperatures obtained in this evaluation were higher than the temperature range of 30-45 ^{0}C which is required to dry foods and fruits (Mercer, 2012) and maintain the product quality (Kadam *et al.,* 2012). The designed solar dryer has capacity of 20 kg, a drying rate of 0.03201 kg h^{-1}, drying efficiency of 56 % with air mass flow rate of 0.025 kg s^{-1} which is comparable to Aliyu (2013). The pineapple slices were dried to the recommeded moisture content of 13% faster than in the natural convention drying method. There was also substantial drop in ascorbic acid content from 38.1 mg/100 g for fresh ripe pineapple to as low as 10.2 mg/100 g for dried pineapple of natural convection drying and highest value of 23.6 mg/100 g for forced air drying.

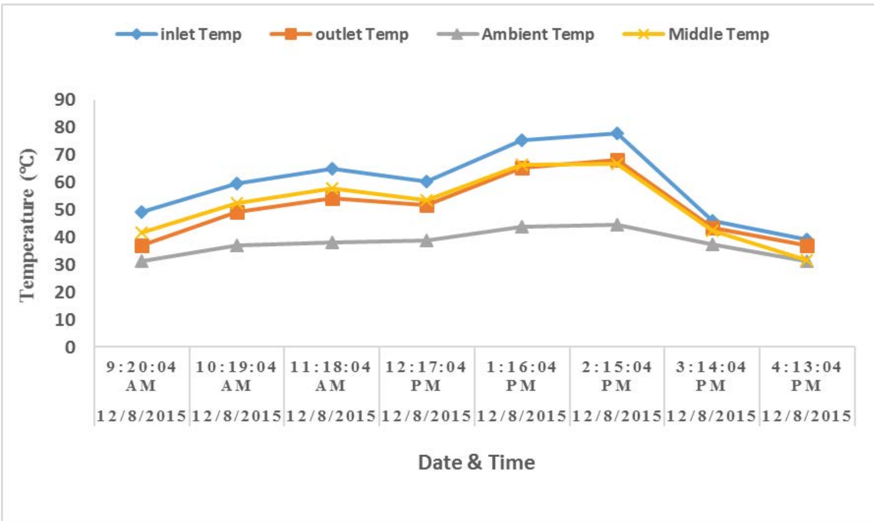


Figure 4: Profile of temperature distribution in and around the forced convection dryer

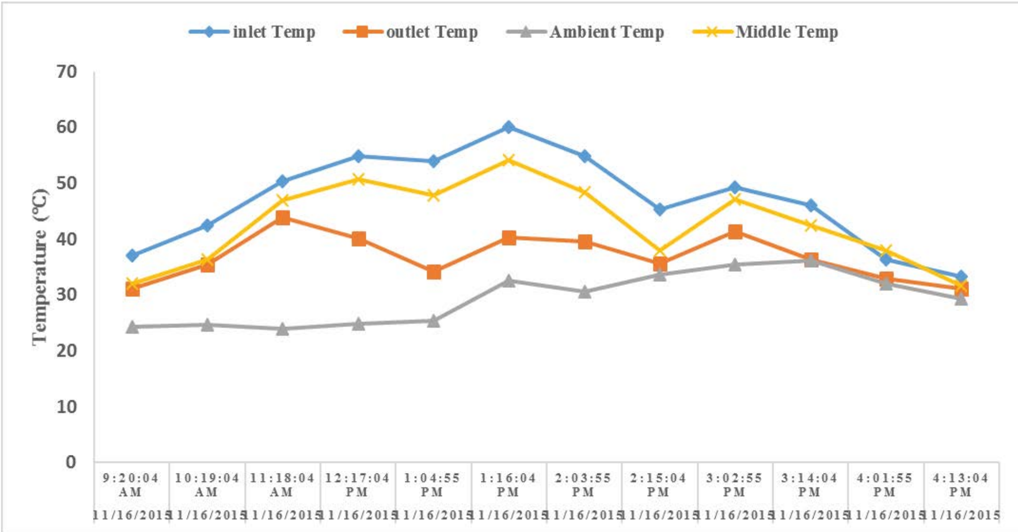


Figure 5: Profile of temperature distribution in and around the Natural convection dryer

Based on the interactions with stakeholders, the new solar cooker-dryer design that has been sketched (Fig. 6) consists of a concrete base of 4 m × 3 m ×10 cm, with a parabolic structure made of silver painted mild steel because of its relative cheapness and availability and covered with a 200 µm transparent UV-stabilized polythene which protects the products together with the structure frame from adverse weather conditions like dust and rain. It also retards the heat from escaping by acting as a heat trap for infrared (thermal) radiation (i.e., forming a confinement for heated air). It also has an airflow system with a solar powered fan for forcing the heated air through to the drying chamber, a delivery tube, flue gas chimney to prevent filtration of smoke into the drying chamber.

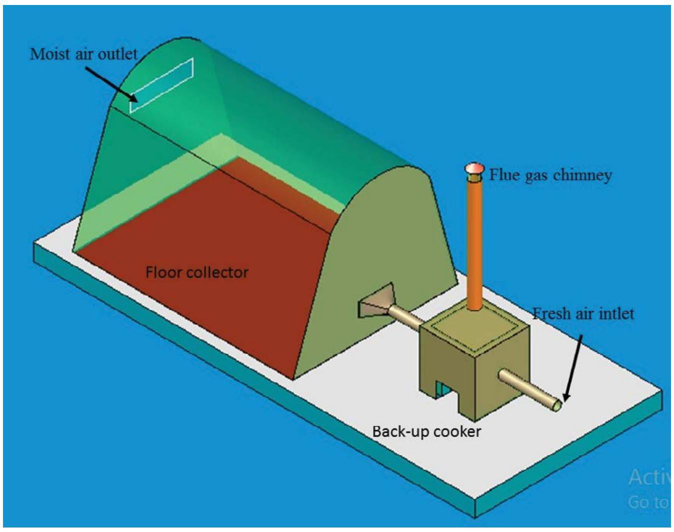


Figure 6: The proposed designed solar integrated cooker dryer

Consequently, the height of the flue gas chimney was set to an appropriate height. Solar powered suction fans that create a draught that enables heated air to flow upward in the PVC black tiled solar collector, passing through the food stuffs arranged in trays was also included. A backup cooker was also included. This is an enclosed rocket stove with a stainless steel pipe 100 mm diameter acting as passage for the heated air. In case of low solar irradiation during the day or if there is need to reduce drying time or ensuring night drying process, the drying process can be backed up by a biomass heater which heats up the air before it passes through the drying chamber. This will mainly address the limitations of the natural sun drying for example drying exposure, liability to pests and rodents, over-dependence on sun and escalated cost of mechanical dryers.

OpenFOAM CFD model output results

A summary of the CFD simulations results is shown in Table 1. The temperature in the back-up cooker was kept at 473 K, the collector floor heated to a maximum of 327 K, while the entrapped air in the drying chamber reached an average of 338 K compared to the 324 K obtained by Galyaki (2016) and 315K obtained by Adeniyi *et al.* (2012) in a simple passive indirect solar dryer. The results obtained closely agree with the 330 K obtained by Dhanushkodi *et al.* (2016) as mean temperature of the air inside the drying chamber in simulation study of a solar biomass hybrid dryer for drying cashew kernel.

Table 1. Important parameters at critical points on the solar cooker-dryer

Point of measurement	Temperature (K)	Velocity (ms^{-1})
Absorber floor	327	
Airflow delivery pipe	338	
Glazing (Visqueen)	316	
Inlet	300	2.00
Drying chamber	330	0.68
Outlet	322	2.15

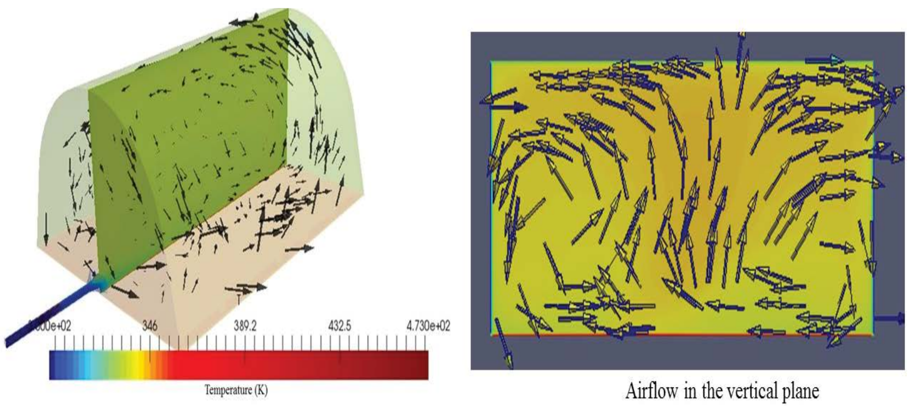
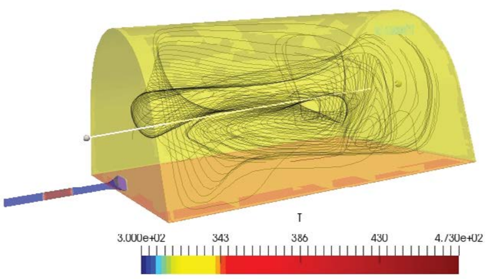


Figure 7. Temperature (K) distribution contours and airflow in the drying chamber



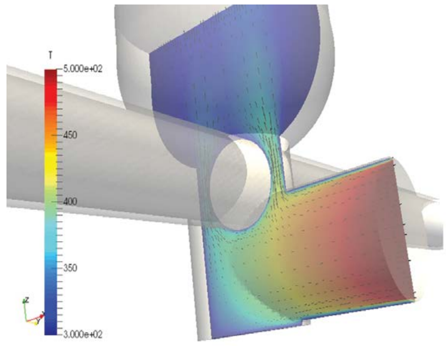


Figure. 8 Contours of Velocity magnitude (ms^{-1}) Figure. 9 Temperature inside the biomass channel

Small magnitudes of the turbulence kinetic energy indicate stability of the flow. The maximum value obtained during simulation is 3 m^2/s^2, which indicates stable air flow. Therefore, since drying in this system is effected by hot air streams, it is clear that uniform drying can be achieved using this design.

Conclusion

The results showed a considerable advantage of forced air solar dryer over the natural convection solar dryer in terms of drying rate and reducing risk of spoilage of pineapple chips. In view of alleviating the weather restriction experienced by farmers in crop drying especially for pineapples it is recommended that the dryers be designed with backup cooker for supplementing solar energy. With the backup cooker, the dryer system will be able to maintain consistent air temperature inside the dryer and significantly reduce drying time. Employing the cooker system and the enhanced airflow increases the drying air temperature which results into increase in the drying rate in two ways. First, it increases the ability of drying air to hold moisture. Secondly, the heated air will heat the product, increasing its vapor pressure which ultimately drives the moisture to the surface faster. Simulation results showed that the incorporation of the cooker raised temperature in the drying chamber to as high as 65^0C, and that with the forced system, there is a relatively uniform temperature distribution.

Finally, a hybrid solar cooker-dryer system has been designed and constructed using simple materials and skills addressing the major challenges faced by the local farmer. The constructed system can overcome the overreliance on natural prevailing weather conditions, as well as providing a hygienic environment for pre-dying processes. The dried products from the hybrid prototype were within acceptable moisture content limits (12-15 %) for safe storage. Products were also of acceptable nutritional quality.

Acknowledgement

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