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Thermal Analysis of Tilapia Fish Drying by Hybrid Solar Thermal Drying System

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ABSTRACT

The present work presents a hybrid solar thermal drying of Tilapia fish to improve the product quality and satisfy the importers. The developed hybrid dryer utilized direct solar drying, a solar air heater and a thermal backup unit which sustains the drying process during the night, cloudy and rainy weather conditions. Besides, a new feature of the developed dryer utilizes the flue gas exhausted from the thermal unit to enhance the updraft in the drying chamber by re-injection of the flue gases in the chimney. The initial moisture content of the Tilapia fish used in the investigation was 246.6% on a dry basis, equivalent to 74% on a wet basis. The investigations were repeated three times on different days. Experimental results showed that the moisture content was reduced to an average final of 17.0% db (5.0% wb) within 17.5 hours, while in the open sun drying, it required around 48-72 hours. Hybrid solar drying required around 72% shorter time than open sun drying. The average overall drying efficiency of the developed system for drying Tilapia fish was 13.0%. The Re-injection technique used in the present hybrid solar-thermal system has excluded the need for an electric source for air extraction from the drying chamber, which is highly desired in the rural and fishery regions.

1. Introduction

Generally, drying is a traditional dehydration process in fish and crops to deactivate the enzymes and remove the moisture to inhibit the growth of microorganisms. Drying may be achieved by electrically heated air, electric ovens, microwave, and solar energy. Electric power in rural areas is either unavailable, unreliable or, for many farmers, is too expensive. Alternatively, solar energy represents great potential for many low-temperature applications in rural areas. Rural farmers have widely utilized the traditional open sun drying to dry agricultural products and fish. Open sun drying has inherent limitations like high crop losses after inadequate drying, fungal attacks, insects, birds, and unexpected weather changes. Various drying techniques have been employed to dry different food products. Each technique has its own advantages and limitations.

1.1 Background on Hybrid Solar Drying

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Lingayat *et al.,* [1] summarized the solar drying technology and all development in a review article. They concluded that the solar dryers assisted with thermal energy storage (TES) systems helped decrease the total time required for drying. The use of hybrid solar dryers (such as dryers with LPG water heaters, diesel burners, and biomass-fueled air heaters) helped satisfy the electrical power requirement so that the dryer could work round-a-clock.

Hybrid solar with biomass stoves could extend the drying period beyond sunshine hours and perhaps during the night and dry high-value products. To reduce its dependence on solar radiation for operation and to improve the quality of drying, a biomass stove was incorporated with a solar drier to introduce a sort of hybrid drying technique, as have been adopted by Bena and Fuller [2], Tarigan and Tekasakul [3], Prasad and Vijay [4] and Singh and Kumar [5]. Biomass fuel, especially wood, is a dominant energy source and is commonly burned using inefficient technologies in most developing countries, as Bena and Fuller [2] and Kaygusuz and Türker [6] reported.

In Aceh Province - Indonesia, the production of catch fishery reached 185 thousand tons. Post-harvesting drying is necessary for transport and a longer reservation period. Hamdani *et al.,* [7] reported a new hybrid solar dryer integrated with a thermal backup unit using wood as fuel. The financial analysis for a dry fish with a production capacity of 12,000 kg per year, selling price 3.3$/ kg, IRR = 18.61%, NPV = $ 21.091 and break-even point = 2.6 years.

Nukulwar and Tungikar [8] reported a new solar thermal drying system by integrating the solar dryer with a copper coil installed underneath the drying chamber. Steam is generated from a Scheffler solar system and circulated in the copper coil. They used the system for turmeric blanching. They claimed an average drying blanching efficiency of 19.93%.

da Silva *et al.,* [9] assessed the performance of a hybrid forced ventilation solar dryer to dry corn grain. The dryer components of a drying cabin, PV system, solar collector. Two fans and an electrical heater were used sustain warm environment inside the cabin to prevent re-absorption of moisture by the corn grain. The corn grains were dried from an initial of 23% to final of 13% moisture contents in 8.5 hours, with drying efficiency of 6%.

Mohd Noh *et al.,* [10] developed industrial scale hybrid solar dryer for sericite mica drying. The hybrid solar dryer consists of evacuated tubes, heat exchanger, blower and drying chamber. The evacuated tube absorbs the solar irradiation and heats water, which is flowing in the piping system. A heat exchanger transfers the heat from the water into the air and the blower produces an air flow with a speed of 3 ms-1 into the drying chamber. Many operational cases have been tested. The main advantage is the intermittent operation mode of the blower which saves electrical energy compared to continuous blower turn on mode.

1.2 Background on Fish Drying

Fish processing includes fish scaling, if necessary, evisceration, washing and draining before sun-drying or smoke-drying. For sun-drying, fish are exposed to sun, and free air and are turned over from time to time for 48-72 hours, depending on the size of fish and the solar irradiation. Smoking drying is carried out in terracotta smoking rooms using various wood species. Fish are smoked for 2-3 h at 70-80°C, followed by mild smoking (30 - 35°C) for 24-48 h, as Ali *et al.,* [11] recommended.

The convective heat and mass transfer coefficients of minor fish species like prawn (invertebrates) and chelwa (vertebrates) have been determined by Jain [12] under solar drying conditions at different drying times and moisture contents. The researcher found that convective heat and mass transfer coefficient values varied significantly with the fish's porosity, shape, size, and initial moisture content. Then, freshwater prawn (Macrobrachium lamarreii); invertebrate and Indian minor carp, chelwa (Oxygaster bacaila); vertebrate fish were considered for study under open sun drying by Jain [13]. The average fish radii were 3 and 4 mm of prawn and chelwa fish, respectively. The drying rate curves contained no constant rate period and showed a linear falling rate throughout the drying process. The time required to reach the equilibrium moisture content was 12 and 18 hours for prawn and chelwa fish.

Bala and Mondol [14] conducted an experimental study on the solar tunnel dryer for drying fish. The fish was initially treated with dry salt and stacked for about 16 hours before drying. The salt-treated fish was dried to a moisture content of 16.8% (wb) from 67% (wb) in 5 days of drying in a solar tunnel dryer compared to 5 days in the traditional method for comparable samples to a final moisture content of 32.84%. Zaman and Bala [15] testified a mixed-mode natural convection solar crop-dryer as potentially most effective to dry agriculture products in humid tropical areas. But mixed-mode drying still has the setback of imposing equilibrium moisture content to the product during the night, with no solar thermal input.

Experimental and theoretical analysis for drying of Tilapia fish was carried out by Kituu *et al.,* [16]. The fish has been cut to 50 mm by 50 mm size and dried in a solar tunnel dryer. They found that the tilapia fish dried to the equilibrium moisture content within two days and nine hours. In addition, they found that the simulated and actual moisture ratios exhibited a similar trend of exponential reduction with drying time.

As a large source of meat in China, osmosis dehydration of tilapia fillets has been extensively studied by Duan *et al.,* [17]. They have studied the effect of hot air-microwave heating on the drying and quality characteristics of fresh tilapia fish fillets. Experimental drying curves were obtained at hot air drying temperatures of 40 and 50 ^{o}C with a constant air velocity of 1.5 m/s. Their experiments showed that hot air drying followed by microwave drying could remarkably decrease the drying time for fresh tilapia fillets than hot air drying. However, microwave operation consumes electric power and may be suitable for a small quantity of tilapia for domestic consumption, not industrial mass production. In 2019, Wang *et al.,* [18] have dehydrated Tilapia fillet by hot-air, vacuum microwave, osmosis microwave and osmosis vacuum microwave to observe the quality and structure of tilapia fillets. They found that the mixed drying method of osmosis vacuum microwave improved showed better quality of the product and comparatively, the fillets are better in terms of microstructure, the per-unit energy consumption of 24.04 kJ/g and color change, 13.8.

Abila [19] found that despite its importance in contributing to national economies, health, food security, and improving the livelihoods of many artisanal fishers in many developing countries, up to 50% of the fish harvested in these countries is wasted. Fish is harvested at an average of high moisture content of 5 kg/kg, db (Garg *et al.,* [20]). If unpreserved, it undergoes rapid spoilage, even without external contamination, in less than 24 hours, as experienced by Gram and Dalgaard [21].

FAO [22] reported that Malaysia's fishery sector is a major source of animal protein to the country's population. In 2017, total fishery production of the country amounted to 1.7 million tons, including close to 1.5 million tons from capture and 0.2 million tons from aquaculture. The fishery industry involved around 132,305 fishers, with an additional 21,156 workers engaged in aquaculture full-time jobs. Unfortunately, the fisheries still use open sun drying, requiring 48-72 hours for equilibrium moisture content.

Therefore, the present work selected Malaysia Tilapia fish for the drying investigation using a hybrid solar drying mode. The drying performance results are presented regarding rate moisture reduction, i.e., drying rate and drying efficiency. The experiments have been repeated three times, at different dates.

2. Methodology

Selection of the right drying techniques is an important matter in the drying process of perishable products. As discussed in the introduction, solar drying has the setback of non-continuous drying, and the hybrid is the appropriate solution. To improve the quality of drying, integration of solar with a stove or biomass fuel burner, especially wood, could extend the drying period beyond sunshine hours, and perhaps during night, as well as dry high-value products. This technique of integration is called hybrid solar-thermal drying.

This section presents the system description, operational principle, experimental setup, and measuring instrumentations. The developed system for the present application is a hybrid solar-thermal dryer consists of a solar collector, drying chamber and thermal backup unit.

2.1 Description of the Hybrid Solar Thermal Dryer

A developed hybrid solar-thermal drying technique has been used in the present characterization of Tilapia fish drying. A hybrid solar-thermal drying system was designed and constructed to operate under a mixed solar mode natural convection integrated with a thermal backup unit. The natural convection solar dryer comprises a single-pass double flow solar air heater (SAH) and drying chamber. The thermal backup unit comprises a gas-to-gas heat exchanger and fuel burner. The flue gases exhausting from the thermal backup unit were guided and injected inside the upper part of the chimney to enhance the stack effect caused by the rise in temperature and reduction density.

The SAH was constructed from the galvanized plate and Aluminium angles, with external dimensions of 1750 mm x1100 mm x140 mm as length, width, and depth, respectively. The 1 mm black painted Aluminium absorber plate was positioned inside the collector with 60 mm and 30 mm gaps between the cover and the absorber and between the absorber and the back. Mathu and Mathur [23], through experimental investigations, reported that the optimum inclination at any place varies from 40° to 60° depending on the latitude and Al-Kayiem and Yassen [24], through experimental investigations, found that 40^o to 50^o inclination was superior compared to 30^o and 70^o inclination, the SAH was tilted by 40^o from the horizontal, facing the south.

The drying chamber was constructed from Aluminium bars with 1100 mm x 420 mm x 900 mm width, depth and height, respectively. The solar collector was directly connected to the drying chamber. There were three portable drying trays with 0.9 m^2 total effective drying area.

The Thermal Backup Unit (TBU) comprises two parts, burner and gas-to-gas heat exchanger (HEX). It burns the fuel and produces flue gas. Figure 1 shows the configuration of the TBU. The detailed design of the TBU, testing, and characterization are reported in further detail by Yassen *et al.,* [25].

In the present drying investigation, a unique technique has been developed to enhance the performance of the drying process. The flue gas produced from the TBU was directed and re-injected inside the chimney at the upper part to increase the natural stack effect caused by the rise in drying air temperature and reduction in pressure. This approach enhances the circulation of warm air in the drying chamber and eliminates the need for an electric extraction fan. Figure 1 shows the schematic diagram, with the dimensions, of the Flue re-injection unit. In a previous independent experimental evaluation, Yassen and Al-Kayiem [26] investigated the effect of the re-injection unit on the drying performance. They found that the overall drying efficiency of the dryer has been enhanced by 6%.

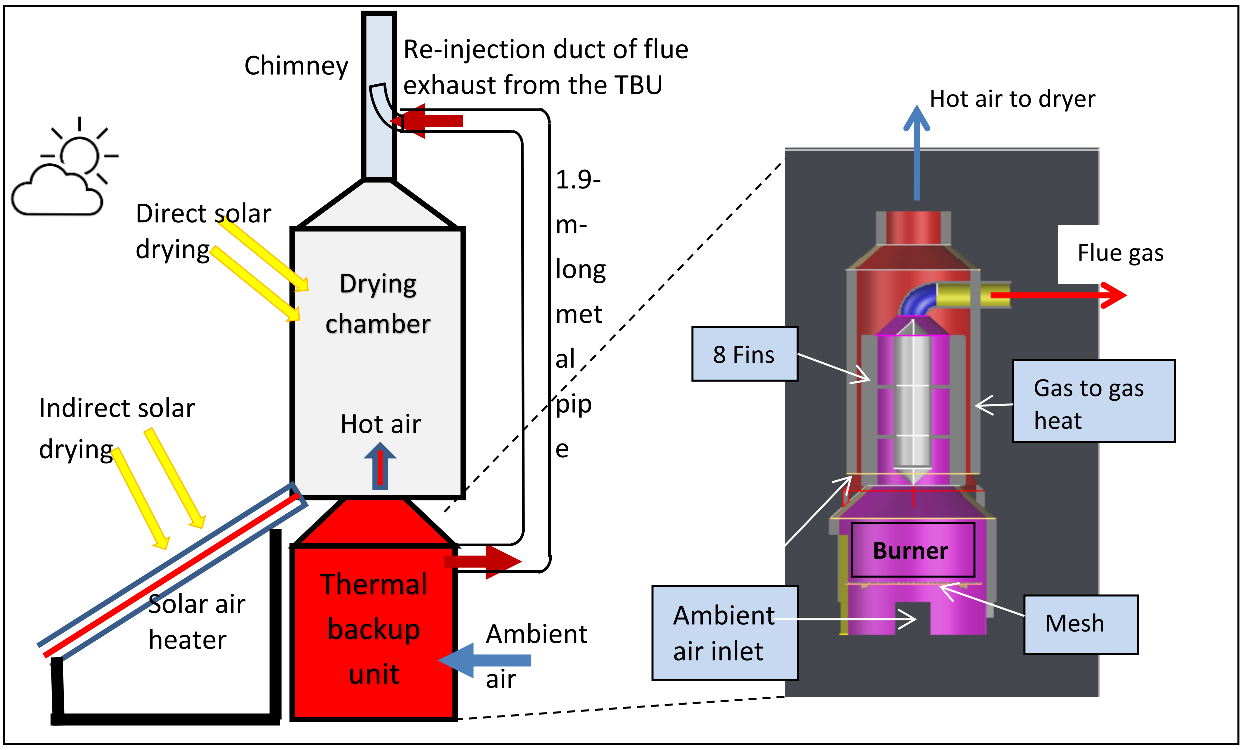

Fig. 1. Schematic diagram of the setup exploring the idea of the flue Re-injection unit

1.1 Operation of the Hybrid Drying System

On rainy and cloudy days and at night, the TBU would supply the hot air to the dryer to indemnify the continuity of the drying process. The biomass fuel was combusted in the burner. The HEX was designed to extract the thermal energy from the hot flue gas and transfer it to the air in the system through 8 extended surfaces. Therefore, the fish was protected from contamination by the smoke and ash. The hot air rises from the gas-to-gas HEX by natural convection and enters the dryer to pick up the moisture from the fish. Madhlopa and Ngwalo [27] suggested recirculating the exhaust gases around the chimney of the dryer to avert reverse thermo-siphoning at night or during periods of low solar irradiation. The recommendation was adopted in this project in another method. The flue gas exhaust from the thermal backup unit was directed to the flue re-injection unit in this developed hybrid dryer. The exit of the flowing gas from the gas-to-gas HEX was injected in the mid-height of the dryer chimney, as shown schematically in Figure 1. This is to permit the flue gas to flow up in the chimney to enhance the extraction of the drying air from the chamber to enhance the natural updraft of the drying air inside the drying chamber.

2.2 Measuring Instrumentations

A calibrated thermocouples wires, type-K-probes (Chromal–Alumal), which can measure temperature in the range -50 to 1000 ^{o}C with accuracy ± 0.1 ^{o}C, have been used to measure the temperature at various locations in the system. The temperatures were measured just above the trays, at the collector and chamber's connection point, and the flue gas's injection point in the chimney. Also, a calibrated thermocouples wires, type-K-surface have been used to measure the surfaces' temperature at different locations inside the dryer. All of the thermocouples were connected to a data logger type GRAPHITIC GL820-UM-851 with 24 input channels. A solarimeter type KIMO SL200 measures solar irradiance in a range of 1 to 1300 W/m^2 with an accuracy of ±5.0%

of reading used to measure the solar irradiation. A digital weight measuring machine, with an accuracy of 0.001 kg in a range of 2.0 kg, has been used to measure the weight of the feeding fuel and samples of the tilapia fish. A Pitot static tube, connected to a digital manometer, has been installed in the chimney to measure the air velocity and then predict the flow rate.

2.3 Measurement Procedure

The experimental measurements by the hybrid solar thermal system have been conducted in the Solar Research Site at Universiti Teknologi PETRONAS – Malaysia. The site is located at a latitude of 4.39° N and a longitude of 100.9° E. Three trials have been repeated to investigate the drying of tilapia fish with the hybrid operation mode. The first experiment (EXP.1) was carried out on 7th February 2016, the second experiment (EXP.2) on 16th February 2016, and the third experiment (EXP.3) on 18th February 2016. The dryer was charged with 6 kg of salted fish spread on the dryer's three trays for each experiment. Twenty pieces, each weighed 100 g, with a total weight of 2 kg, have been spread in each tray. Every single fish was cut into four pieces. The sample of 100 g in each tray was used to conduct the drying rate. Here, the recommendation of Sengar *et al.,* [28] was adopted as they found that the salted, dried fish is better than unsalted fish for its color and texture. Hence, every single piece was salted before the experimental commencement. All experiments were starts at 9:00 am morning and ended at around 3:00 am after midnight.

The tilapia fish samples were located between the center and each tray's edge to determine the mean drying rate at each dryer level. A 100 g initial weight sample was selected, and then measurement was taken every 2 hours and weighed to reduce weight to predict the drying rate. The biomass fuel was burned in the Thermal Backup unit during the night to provide the required hot drying air. The weight of the biomass was measured using digital weight balance before feeding to the TBU. The feeding of the fuel was repeated each hour. The fabricated setup of the hybrid solar dryer is shown in Figure 2.

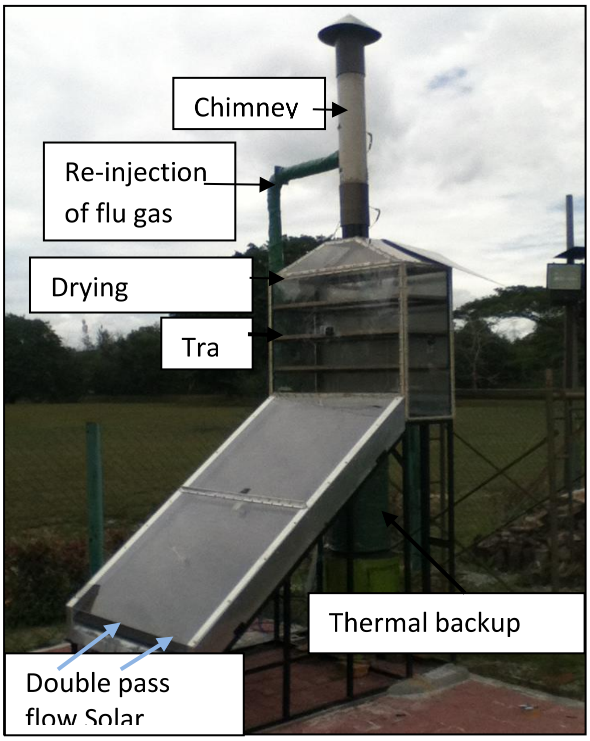

Fig. 2. The experimental hybrid dryer test rig

3. Results

3.1 Evaluation of the Initial Moisture Content

The initial moisture content in the crop can be evaluated on a wet basis (wb) and stated in percent. For each experiment, a sample of initial weight w_i was subjected to drying in a convective electric oven, whose temperature was maintained at 105 °C. The weight of the sample was checked every 1 hour. When the change in the weight difference was negligible, the process was terminated by switching off the oven, and the final weight, w_d (kg), of the sample was recorded. The moisture content of the sample, M_i (kg/kg) on a wet basis was calculated using Eq. (1)

$$M_i = \frac{w_i - w_d}{w_i} \quad (1)$$

The calculated initial moisture content of the Tilapia fish using Eq. (1) was 246.6 % based on a dry basis (db), which is equivalent to 74% based on a wet basis.

3.2 Weather Conditions

The hourly variations of the measured solar irradiance and ambient air temperatures for the three experiments are shown in Figure 3. The maximum solar irradiance values of EXP.1, EXP.2, and EXP.3 were 937, 1045, and 920 W/m^2, respectively. The maximum ambient temperature values were 36.4 °C, 36.0 °C, and 36.3 °C, for EXP.1, EXP.2, and EXP.3, respectively. The minimum ambient relative humidity during the days of the three experiments was in the range of (43-50) %. The maximum ambient relative humidity during the nights of the three experiments was (91-93) %. The odd values of the solar irradiance values were due to the presence of clouds during the experiment.

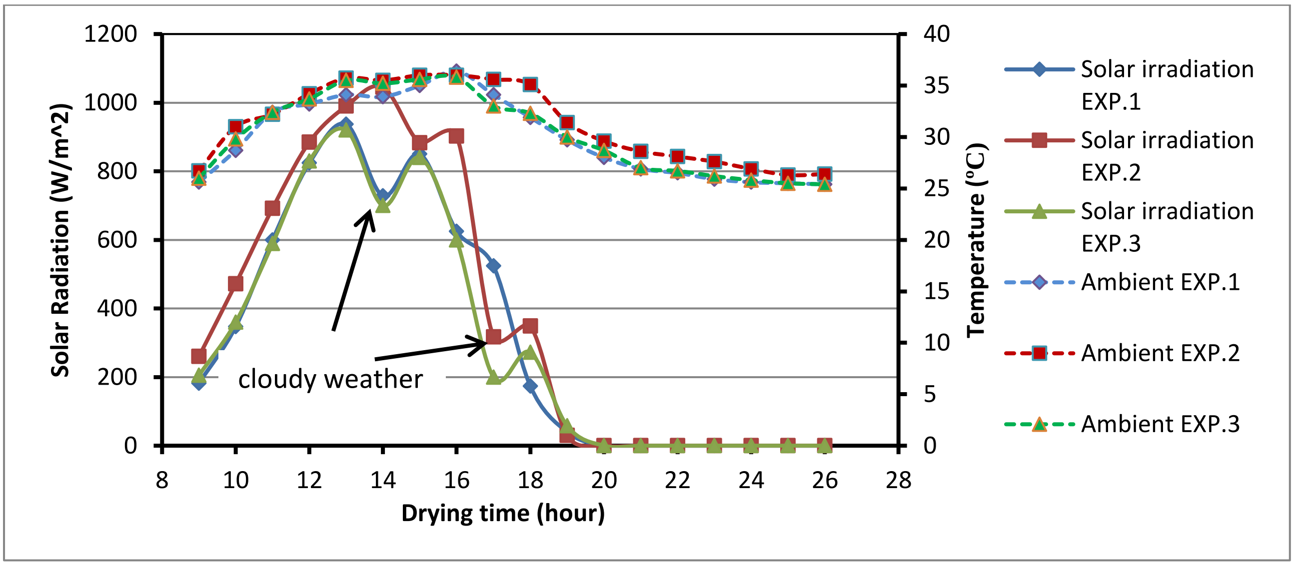

Fig. 3. Variations in solar irradiation and ambient temperature with the drying time of fish in the three experiments (February 7^{yh}, 16th, and 18th, 2016)

3.3 Dryer Thermal Conditions

Figure 4 shows the average dryer and ambient temperatures variations with fish drying time in the three experiments. The results indicated that the average dryer temperature in EXP.2 was higher than the average dryer temperatures of EXP.1 and EXP.3 because the solar irradiation during EXP.2

was higher than that in EXP.1 and EXP.3. The average dryer temperature also declined as sunset approached.

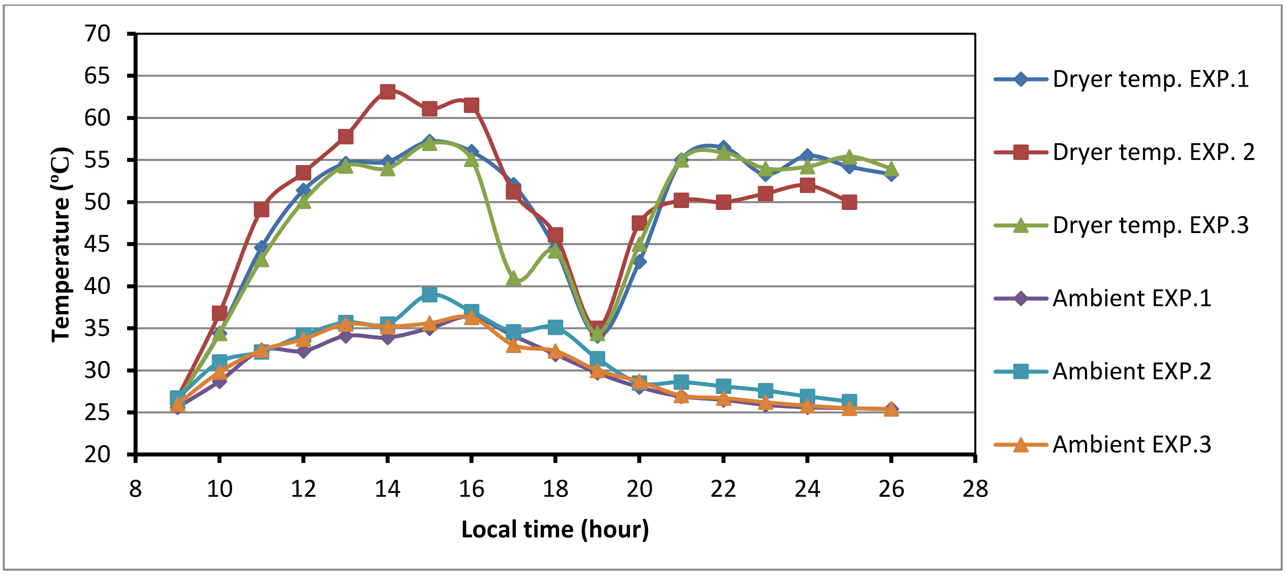

Fig. 4. Variations in the average dryer temperature in the three experiments, from 9:00 am to 2:00 am after midnight for drying Tilapia fish. (7th, 16th, and 18th February 2016)

The maximum average dryer temperature of EXP.2 was 63.0 °C at 2:00 pm. The maximum average dryer temperature of EXP.1 was 57.2 °C at 2:00 pm. The maximum average dryer temperature EXP. 3 was 57 °C at 3:00 pm. The maximum average dryer temperatures at night for EXP.1, EXP.2, and EXP.3 were 56.5, 52.0, and 55.9 °C, respectively. At 7:00 pm (starting of thermal mode), the ambient temperatures for EXP.1, EXP.2, and EXP.3 were 29.7, 31.4, and 30 °C, respectively. The ambient temperature of EXP.1, EXP.2, and EXP.3 at night declined to minimum values of 25.4, 26.3, and 25.4 °C, respectively.

3.4 Tilapia Drying Conditions

The moisture content reductions in the three experiments of drying Tilapia fish are shown in Figure 5. The initial moisture content of the fish used in the experiments was 246.6% based on a dry basis (db) (equivalent to 74% based on a wet basis (wb)). The sample's moisture content in EXP.1 was reduced to the final moisture content of 19.3% (db) (5.8% wb) within 18 hours. The sample's moisture content in EXP.2 was reduced to the final moisture content of 11.36% (db) (3.4% wb) within 16.5 hours. The sample's moisture content in EXP.3 was reduced to the final moisture content of 19.5 (db) (5.85% wb) within 17.5 hours. The drying rates of EXP.1 and EXP.3 were similar because the solar irradiation values in both experiments were also similar, as shown in Figure 5. The global solar irradiation values for EXP.1 and EXP.3 were 5.850 and 5.744 kWh/m^2, respectively. The global solar irradiation value for EXP.2 was 6.868 kWh/m2. The drying rate for EXP.2 was faster than the other experiments because the solar irradiation value was higher, as illustrated in Figure 3.

The drying rate in the three experiments of drying the tilapia fish is presented in Figure 6. For EXP.1 and EXP.3, the constant drying rate period has appeared within the first five hours of drying with high moisture content. Because the fish was salted before being inserted in the dryer, therefore there is high surface water. It is leading to a high drying rate. The drying rates for EXP.1 and EXP.2 were around 0.3 g water/g dry matter during the drying rate. After five hours, the first failing drying rate period was start and end at ten hours. After ten hours of drying, the second failing drying rate period started and continued to the experiments' end. For EXP.2, the constant drying rate period not appeared within the first five hours due to high solar irradiation compared with EXP.1 and EXP.2. Therefore, through EXP.2, the first failing drying rate period appeared from the start of the experiment until the end of the first ten hours. After ten hours of drying, the second failing drying rate period has appeared. The constant and first falling drying rate period has appeared within the solar mode of operation. The second failing drying rate period has appeared within the night mode operation. The drying rate decreased as the drying time increased and moisture content decreased.

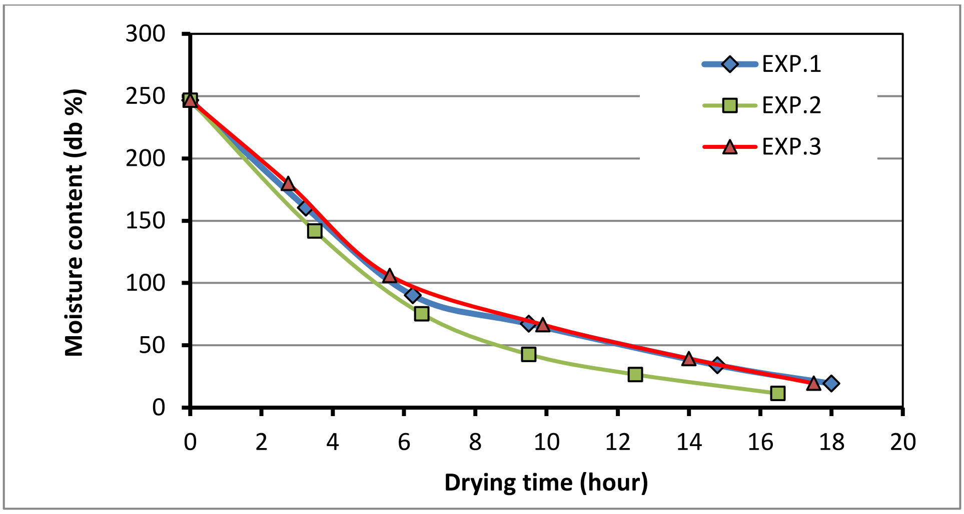

Fig. 5. Variations in the moisture contents of drying fish for the three experiments (7th, 16th, and 18th February 2016) with time

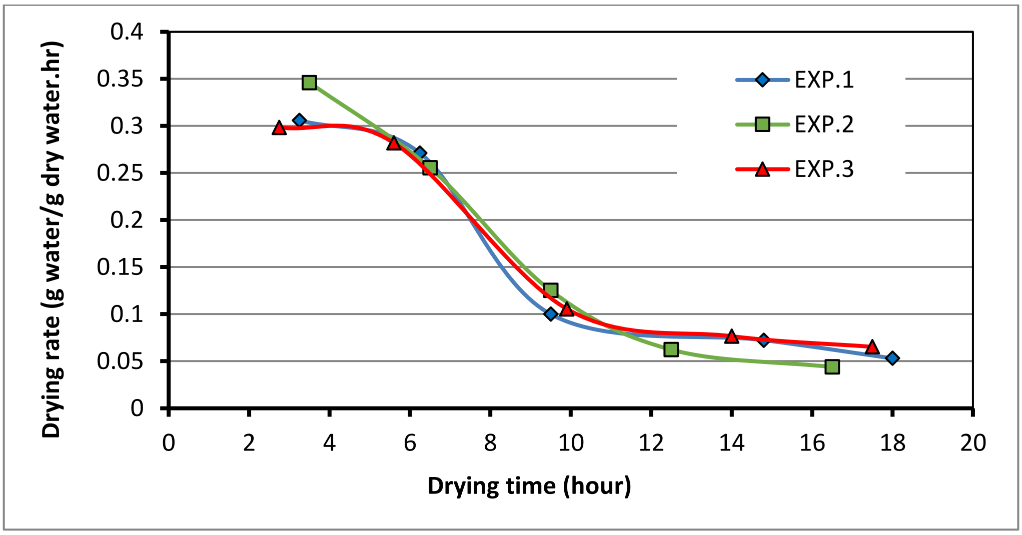

Fig. 6. Variation in the drying rate over time for the three drying Tilapia fish experiments (February 7th, 16th, and 18th, 2016)

The developed system and procedure reduced the required drying time considerably. In the present experiments, the mean time required to dry the fish using a solar-thermal drying system is around 18 hours. The reported time for open sun drying of Tilapia fish is around 48 to 72 hours, depending on the solar irradiance, Ali *et al.,* [11].

3.5 Overall Drying Efficiency

The overall drying efficiency over entire drying trails is the ratio of the energy used to evaporate the moisture from the crop to the energy supplied to the dryer; both solar radiation and biomass supplied the energy. The overall drying efficiency of the dryer is computed by using the procedure reported by Bena and Fuller [2] and Leon *et al.,* [29]

$$\eta_d = \frac{m_w h_{fg}}{I_g A_T + C_v w_{bs}} \quad (2)$$

where
I_g: Global solar irradiation during the trail, kWh/m^2
C_v: Calorific value of biomass, kJ/kg
w_{bs}: Weight of the biomass, kg

Table 1 shows the overall drying efficiency of drying fish (EXP.1, 2nd February 2016). In this experiment, the global solar irradiation received was 5.850 kWh/m^2 during the day. The amount of wood that was burned at night was 1.9 kg. The calorific value of the wood was 17295 kJ/kg, according to experimental characterization by Yassen and Al-Kayiem [26]. The amount of moisture that was removed from 6 kg of fish was 4.09 kg. The overall drying efficiency of the system for drying fish was 12.75%.

The overall drying efficiency of drying Tilapia fish of EXP.2, 16th February 2016 is shown in Table 1. In this experiment, the received global solar irradiation during the day was 6.868 kWh/m^2. The amount of wood that was burned at night was 1.4 kg. The amount of moisture that was removed from 6 kg of fish was 4.2 kg. Therefore, the overall drying efficiency of the system for drying fish was 13.3%.

The overall drying efficiency of drying Tilapia fish of EXP.3, 18th February 2016 is shown in Table 1. In this experiment, the global solar irradiation received during the day was 5.744 kWh/m^2. The amount of wood that was burned at night was 1.9 kg. The amount of moisture that was removed from the 6 kg of fish was 4.1 kg. The overall drying efficiency of the system for drying fish was 12.9%.

Table 1
Overall drying efficiency of drying Tilapia fish (EXP.3, 18th February 2016)

Experiment	I_g (kWh/m^2)	h_{fg} (kJ/kg)	m_w (kg)	w_{bs} (kg)	C_v (kJ/kg)	η_d (%)
EXP. 1 7 Feb. 2016	5.850	2501	4.09	1.9	17295	12.75
EXP. 2 16 Feb 2016	6.87	2501	4.2	1.4	172,95	13.3
EXP. 3 18 Feb 2016	5.744	2501	4.1	1.9	172,95	12.9

From the three experiments, it could be concluded that the increase in solar irradiance also decreased the weight of the biomass that was burned and increased the overall drying efficiency.

3.6 Justification of the Results

The justification of the experimental work has been achieved by comparison the drying time with the previous works for drying Tilapia fish, as shown in Table 2.

Table 2
Comparison between the present hybrid solar drying with open sun and other drying techniques

Research	Investigation technique	Drying technique	Drying time (Hours)	Conditions	Remarks
Kituu *et al.,* (2010) [16]	Experimental and theoretical	Natural convection in a solar tunnel dryer	57 hours in the dryer	The fish has been cut to pieces of size 50 by 50 mm	The simulated and actual moisture ratio exhibited a similar trend of exponential reduction with drying time
Ali *et al.,* (2011) [11]	Experimental	Open sun drying	48 -72	Fish were scaling evisceration, washing and draining. Fish were exposed to sun, and free air and are turned over from time to time during the experiment.	Highly depend on solar irradiance and ambient temp.
Ali *et al.,* (2011) [11]	Experimental	terracotta smoking-rooms	26 -51	Fish was scaling evisceration, washing, and draining. Fish are smoked for 2-3 hours at 70-80 °C, followed by mild smoking (30-35 °C) for 24-48 hours.	
Duan *et al.,* (2011) [17]	Experimental	Hot air followed by microwave drying	4 hours drying in an electric oven, then 2, 4, 6, 8,10 minutes in microwave. 19 hours if only electric oven used	Tilapia fish were cleaned, gutted, skinned, and headed, then cut into fillets with the size of 30 × 20 × 3 mm. They were then placed in a single layer on a stainless steel wire mesh for drying experiments.	Samples were dried at 200, 400 and 600 W of microwave power after pre-drying at 50 °C. microwave drying shortens the drying time greatly compared to hot air drying of tilapia fillets
Hamdani *et al.,* (2018) [7]	Experimental	Solar dryer integrated with wood-fuelled TBU	19 hours	Medium size Queenfish is cleaned from the scales and gutted, then split into two. Then the fish was rinsed and weighed to know the overall weight of the whole fish. Fish weighing 26 kg, arranged in a drying rack for drying until the final moisture content is about 10–12%.	The designed and fabricated hybrid dryer is capable of drying the fish for 15 hours, with the final moisture content in the fish around 12%
Present work	Experimental	Hybrid solar thermal dryer	18 hours	A biomass thermal source backed up the solar dryer. Each fish was cut into four pieces, salted, and spread in one layer in the three trays. A sample of 100 g initial weight was used to measure the drying rate.	Continuous drying, by hybrid mode, is very effective. The mean overall drying efficiency is 13.0%. The TBU reduces the drying time by 70% compared with solar drying.

Duan *et al.,* [17] found that the tilapia fish dried to equilibrium moisture content within 57 hours from his experimental measurement results. In the present work, the tilapia fish was dried to equilibrium moisture content within 17 hours. Therefore, the present hybrid solar drying system with the hybrid drying mode (continuous drying) reduced the drying time by approximately 70% compared with solar mode drying in the solar tunnel dryer by Duan *et al.,* [17]. While the reported time for open sun drying of Tilapia fish is around 48 to 72 hours, depending on the solar irradiance, as reported by Ali *et al.,* [11]. Hamdani *et al.,* [7] developed a new hybrid solar dryer backed up by a biomass air heater to dry Queenfish. They managed to dry the fish to about 10-12% moisture content in 15 hours.

4. Experimental Uncertainty Analysis

An uncertainty analysis is a vital part of any experimental program or measurement system design. Uncertainty may originate from causes, such as inaccuracy in the measurement equipment, random variation in the quantities measured, and approximations in the data-reduction relations. In general, consider R to be a function of n measured variables x_1, x_2, …, x_n; that is

$$R = f(x_1, x_2, \dots \dots, x_n) \tag{3}$$

Then, a small change, δR, in R is caused by small changes δx_i's in the x_i's could be determined through the differential equation suggested by Wheeler and Ganji [30]

$$\delta R = \delta x_1 \frac{\partial R}{\partial x_1} + \delta x_2 \frac{\partial R}{\partial x_2} + \cdots + \delta x_n \frac{\partial R}{\partial x_n} = \sum_{i=1}^{n} \delta x_i \frac{\partial R}{\partial x_i} \tag{4}$$

which might be expressed mathematically, as

$$w_R = \sqrt{\left(\sum_{i=1}^{n} w_{x_i} \frac{\partial R}{\partial x_i}\right)^2} \tag{5}$$

In the present experimental investigation, the measurement variables which contributed to the overall drying efficiency are

- Mass of moisture removed from the material, m_w
- Mass of the biomass fuel, w_{bs}
- The solar irradiation accumulated during the experiment, I_g, and
- The calorific value of the biomass fuel, C_v

To predict the uncertainty in the overall drying efficiency, η_d, using Eq. (5), the partial derivatives of each individual parameter were derived, as in Eq. (6) to Eq. (10).

$$\eta_d = f(m_w, w_{bs}, C_v, I_g) \tag{6}$$

$$\frac{\partial \eta_d}{\partial m_w} = \frac{h_{fg}}{I_g A_T + C_v w_{bs}} \tag{7}$$

$$\frac{\partial \eta_d}{\partial w_{bs}} = -\frac{m_w h_{fg} C_v}{(I_g A_T + C_v w_{bs})^2} \tag{8}$$

$$\frac{\partial \eta_d}{\partial C_v} = -\frac{m_w h_{fg} w_{bs}}{(I_g A_T + C_v w_{bs})^2} \tag{9}$$

$$\frac{\partial \eta_d}{\partial H} = -\frac{m_w h_{fg} A_T}{(I_g A_T + C_v w_{bs})^2} \tag{10}$$

Hence, the detailed formulation of the uncertainty estimation in the drying efficiency is given as

$$w_{\eta_d} = \sqrt{\left(\left(w_{m_w} * \frac{\partial \eta_d}{\partial m_w}\right) + \left(w_{w_{bs}} * \frac{\partial \eta_d}{\partial w_{bs}}\right) + \left(w_{C_v} * \frac{\partial \eta_d}{\partial C_v}\right) + \left(w_{I_g} * \frac{\partial \eta_d}{\partial I_g}\right)\right)^2} \tag{11}$$

And the accumulated uncertainty is

$$Uncertainty = \frac{w_{\eta_d}}{\eta_d}\, x100 \tag{12}$$

MS Excel has been used to solve the resulted equation and predict the uncertainty of the overall drying efficiency, which was within the range of ± 0.45%. It is low due to the high accuracy of the instruments used in the experiments.

5. Conclusions

A hybrid solar-thermal drying system is developed and continuously drying over day and night, where a biomass burner is used as a thermal backup to supply heat in the night. The system has a new feature of enhancing the natural up drafting by re-injection of the hot flue gases from the burner into the upper chimney, named flue re-injection. The system is evaluated experimentally using Tilapia fish as a drying specimen. The mean overall drying efficiency is 13.0%. The present hybrid solar-thermal drying system reduces the drying time by 70% compared with the solar drying of Tilapia fish reported in the literature. Comparison of results with previous works demonstrates that continuous drying by hybrid solar-thermal is a very effective method in reducing drying time and enhance overall drying efficiency of the system. The flue re-injection technique used in the present hybrid solar-thermal system has eliminated the need for an electric source to extract air from the drying chamber which is highly desired in the rural and fishery regions.

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