ISSN 2738-9898 (Print) ISSN 2738-9901 (Online)

Design, Fabrication and Performance Evaluation of Mixed-Mode Solar Tunnel Dryer for Buffalo Meat by Forced Convection

Siddhartha Paudel, Bibek Dhungana

Department of Mechanical Engineering, Eastern Region Campus, Institute of Engineering, Dharan, Nepal

E-mail: *paudelsiddhartha36@gmail.com*

Received on: 17th May, 2023

Accepted for publication: 11th July, 2023

Abstract

In the context of Nepal, the consumption, as well as preservation of meat products, has been in practice for ages. The primitive approach - open sun drying technique- a technique for preserving meat for longer, can contaminate the meat. In addition, the meat in direct contact with UV rays also degrades the quality of meat which may not be suitable for consumption. Exposing the meat to the open air causes the evaporation of its moisture, leading to a decline in flavour and an extended duration for the dehydration of the meat product. The alternative technique - mixed mode solar tunnel dryer - is a revolutionary method to undertake the challenges, which uses both solar heated air and direct solar energy. This paper majorly includes the design, fabrication and performance evaluation of a solar mixed-mode tunnel dryer by forced convection for buffalo meat. The purposed system was designed for drying 4 kg of meat for humid sub-tropical climatic conditions with an estimated design drying time of 7 hrs 44 mins. The designed system includes a collector of area 2 m², a drying chamber, and a DC fan. The recorded parameters were incident solar irradiance, air temperature, relative humidity of the air, and moisture content of meat at equal intervals. Reducing the moisture content in buffalo meat to 26.78% by weight in the month of November, took a total of 14 hrs with maximum collector efficiency of 29.79%.

Keywords: Forced convection, Mixed-mode solar tunnel dryer, Solar drying, Solar collector.

1. Introduction:

In developing countries, the preservation of meat products is one of the major problems. Large quantities of these products spoil due to inadequate infrastructures, insufficient processing capabilities, and marketing difficulties. As a result, more and more buffaloes are being imported from neighbouring countries to Nepal, to supply fresh meat and also contribute to the market of the nation. The open drying method is the commonly preferred method, as it is cheaper than the solar drying method. In general, drying is the lowering of water activity of perishable products accomplished by removing water, which restricts the growth of microorganisms [1]. The continuous removal of moisture content, air, and temperature of the product simultaneously by placing the product in the open sun is sun drying. Sun drying is effective for buffalo meat, only if the temperature is constant for a long period as the moisture contained in the fresh buffalo meat is 74-78% [2]. The dust and dirt in the environment contaminate the meat and the direct UV rays of the sun reduce the quality of the dried meat. Likewise, liquid components in the meat may evaporate in the open air thereby declining the flavor of the meat. Dried meat is of particular concern because dehydrators rarely reach temperatures beyond 140°F (60°C) [3]. The temperature typically in the dehydrator is not high enough to kill harmful microorganisms that may be present in meat. Since a constant 60°C temperature is needed to dry the buffalo meat, direct exposure to the sun may not fulfill the temperature requirement. The application of solar energy for meat preservation is appropriate for sustainable development [4].

The solar dryer is a highly effective method for producing quality dried meat due to its faster drying rate, which minimizes the meat's susceptibility to decomposition. The flavour and nutritional value of the meat remain higher than the open sun drying. Additionally, the meat remains free from dust and dirt and is not affected by rain. The quality of meat is greater so has a higher market rate in comparison [5]. Solar drying is a continuous process in which moisture content, air and product temperature change simultaneously along with the two basic inputs to systems: the solar insolation and inlet air at ambient temperature. The ambient climatic conditions affect the drying rate. This includes temperature, relative humidity, sunshine hours, solar insolation, wind velocity, frequency and duration of rain showers during the drying period [6].

Solar dryers help to provide more heat than the atmospheric temperature. Engmann *et al*. used a solar drying technique for snail's meat and found the least number of microbial during the storage period of more than 30 days [7]. In a solar dryer, air entering the chamber through a natural convection process or forced convection process gets heated and also partially cooled absorbing moisture from the food placed to dry [8]. In natural convection, dryers run without a pumping source like a fan for the flow of air. The air moves due to the density difference through the heating chamber. This resembles a disadvantage of low air flow rate, long drying time and hence low capacity of drying. Forson et al. fabricated a mixed-mode natural convention solar tunnel dryer for drying cassava seeds. The products were dried in 35.5 hrs., outperforming the open sun drying technique [9]. In forced convection air moves due to the power generated by some external devices like fans, pumps etc. This resembles the disadvantage of the requirement of external power to run the fan since the rural or remote areas of many developing countries do not have the required source of power like electricity. Mondol et al. fabricated the solar tunnel dryer for drying silver jewfish. The dryer outperformed sun drying by about 16% in terms of the final moisture content of fish [10].

Mixed-mode solar has two compartments; the primary collector is an air heater and the secondary collector is a drying unit. Solar energy collection takes place in both the air heater and drying unit, and drying takes place only in the drying unit. In the tunnel dryer, the airflow in a horizontal direction results in the two compartments in series. Recently greenhouse solar dryer has grown its popularity among larger business and agricultural firm, however for household and small business purpose solar tunnel dryer has their own significant economically [11]. Mixed-mode solar tunnel dryers help to remove moisture more quickly than other dryers since they combine both tunnel and mixed-mode dryers [12]. Mixed-mode dryers provide a regulated environment that helps maintain constant temperatures and airflow, improving the quality of the finished product [13]. Lakshmi *et al*. carried out an experimental investigation for drying stevia leaves using a mixed-mode forced convection dryer and compared it with open sun drying where they found better preservation of color and flavour [14].

The meats dried in a dryer also gain better quality without losing their available nutrients which may get a better market value as well. There has been sufficient research carried out in the field of solar dryers. Woranuch designed and tested a solar cabinet dryer and used it to dry pork. The preheating of the ambient temperature greatly enhances the drying efficiency of the dryer. Similarly, the cabinet dryer is found to be suitable for drying products that have an optimum drying temperature of 45ºC - 48ºC [15]. This paper accounts for the design, fabrication and performance of solar dryer for meat preservation in humid sub-tropical climatic conditions.

2. Methods:

2.1. Mathematical Formulation:

Equating, the overall heat gain to the overall heat lost by the heat absorber of the solar collector gives the energy balance of the solar dryer. Therefore,

$$IA_C = Q + Q_{Cond} + Q_{Conv} + Q_{Rad} + Q_M \quad (1)$$

Where, A_c represents the area of the collector (m^2) through which incident radiation I (W/m^2) strike the surface of absorber and Q represents the rate of useful energy collected by the air, Q_M, the rate of losses in the form of reflection from the absorber (W). The conduction, convection and radiation losses are the total heat loss that occurs in the dryer.

$$Q_L = Q_{Cond} + Q_{Conv} + Q_{Rad} \quad (2)$$

If the glazing surface has transmittance τ and also the total solar radiation I_t incident on the glazing surface, the right-hand side of Eq. (1) becomes:

$$IA_C = \tau I_t A_C \quad (3)$$

The absorber absorbs the incident energy and also reflects some sort of energy as they have absorptivity and reflectivity. The reflected energy is given by the expression:

$$Q_M = \rho \tau I_t A_C \quad (4)$$

Where ρ and τ represent the absorber's reflection coefficient and transmittance of the glazing surface respectively. Substitution of the value of Eqs. (2), (3) and (4) in Eq. (1), we get:

$$\tau I_t A_C = Q + Q_L + \rho \tau I_t A_C \quad (5)$$

An absorber doesn't transmit the energy as they are opaque and painted black. So, the sum of absorption and reflection should be one. Therefore, $(1 - \rho) = \alpha$ and hence:

$$Q = \alpha \tau I_t A_C - Q_L \quad (6)$$

Where, α is the solar absorption. Q_L is total heat loss composed of convection, conduction and radiation. It can be represented in the following form:

$$Q_L = U_L A_C (T_C - T_a) \quad (7)$$

Where U_L is the absorber's overall heat transfer coefficient between the collector's absorber temperature T_c (K) and ambient air temperature T_a (K) through area A_C (m^2) of the collector.

From Eqs. (6) and (7) the useful energy gained by the collector is given as:

$$Q = \alpha \tau I_t A_C - U_L A_C (T_C - T_a) \quad (8)$$

If the air having the ambient temperature enters inside the collector from the inlet and air leaving the collector is at outlet temperature, the heat gained by the air when the flow from inlet to outlet is:

$$Q = \dot{m} C_p (T_c - T_a) \quad (9)$$

Where, $\dot{m}$ is the rate of mass flow of air departed from the dryer (kg/s) and C_p specific heat capacity of air at constant pressure (kJ/kgK).

From the first law of thermodynamics, C_p $(T_c\text{-}T_a)$ is equal to $(h_2 - h_1)$. The Eq. (9) becomes:

$$Q = \rho_{air} \times (h_2 - h_1) \times V_{air} \quad (10)$$

Where h_1 and h_2 are the enthalpy at ambient temperature and exit of the dryer respectively, Vair is volume flow rate as it can be written in the form of humidity as $\dot{m}_w/(\rho_{air} \times (x_2 - x_1))$. The collector's thermal efficiency is defined as:

$$\eta_C = \frac{Q}{I_C A_C} \quad (11)$$

2.2. Study Area:

The design of the dryer involves the collection of the climatic data of the study location, i.e., Dharan. Dharan is located in the eastern region of Nepal, at a latitude of 26.793°North and longitude of 87.293°East. The season for the study period is winter.

3. Design Calculation and Considerations:

The designed dryer consists of two compartments, i.e., the primary collector and the secondary collector. The primary collector heats the air which flows through it and the secondary collector contains the tray on which the buffalo meats are placed for drying. The design was done for the month of September-November; the dryer was placed outside with the collector facing towards the sun. The dryer has been fixed at an angle of 30° to the horizontal to obtain the approximately perpendicular beam of sun rays. The drying chamber was designed for 4 kg of buffalo meat. The initial moisture of fresh buffalo meat is 74.04% [16], [17] and final moisture is 23.2% [18] in dried buffalo meat. The area of solar collector is considered as 2 m^2. The primary collector and the secondary collector have area of

1m^2. The average thermal efficiency of a v-corrugated collector is 31.50% [19]. Accounting for possible losses because of fabrication errors, initial design efficiency is assumed to be 30%.

The design was done for the optimum temperature (60°C) for the meat to dry and the ambient temperature (20.33°C) is taken from the weather data (average of months September, October, and November of 2018). The average humidity and temperature of this three month is 74.57% and 20.33°C respectively (Dharan annual weather averages, 2019). The average solar insolation of Dharan is 525.714 W/m^2 [20]. Using 30% thermal efficiency and 2 m^2 area of the collector in Eq. (11), the useful heat energy by the collector is 1135.542 kJ/hr.

3.1 Drying Time:

Based on wet material moisture content, the water that has to be removed is given by [21]:

$$M_w = \frac{W_{in} - W_{out}}{100 - W_{out}} \tag{11}$$

Where, W_{in} and W_{out} are the initial humidity of buffalo meat and the final humidity of dried meat respectively. 0.6619 kg per kg meat water has to be removed. The time need to remove the necessary water from the '4 kg' of buffalo meat was about 't' time and the removed amount is: 0.6619 × 4 kg. The humidity removal rate is:

$$\dot{m}_w = \frac{4}{t} \times 0.6619 \tag{12}$$

3.2 Volume Flow Rate:

Since, the final water content in dried meat was expected to be 23.2%, it was used to determine the water activity of meat as shown in Fig. 1. The water level activity at final humidity during desorption is 0.785. Thus, mean relative humidity of air is 89.25% using water level activity at final humidity.

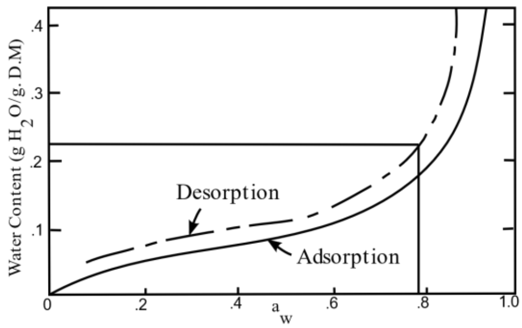


Figure 1: Water activity for meat [22]

During the drying process, initially sensible heating occurs from an ambient temperature of 20.33°C up to 60ºC inside the dryer and then dehumidification of meat starts which is plotted in a psychrometric chart as shown in Fig. 2. From the psychrometric chart, enthalpy (h_1) of ambient air at a temperature of 20.33°C was calculated to be 48.89 kJ/kg and its absolute humidity is 11.20 g/kg at 74.57% relative humidity.

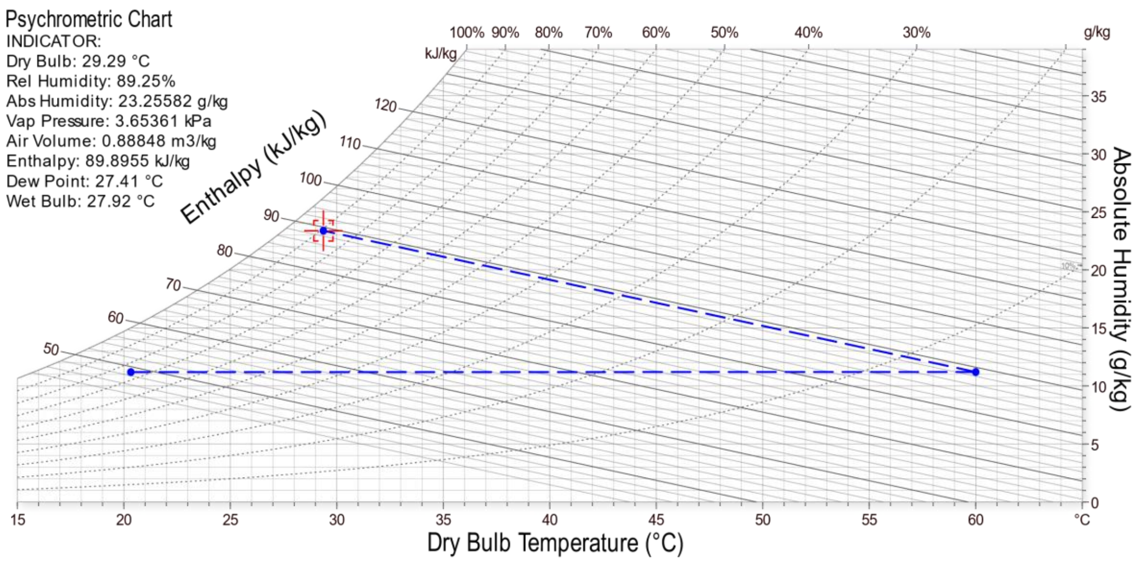


Figure 2: Enthalpy calculation using a psychrometric chart

For mean air humidity of 89.25%, the absolute humidity at the exit of the dryer is 23.25 g/kg. The enthalpy at the exit of the dryer at 60°C is 88.89 kJ/kg. Using Eq. (10), the volume flow rate to dry

4 kg buffalo meat is 23.17 m^3/hr. Relating volume flow rate value with the humidity removal rate and humidity at the initial and final stage, 4 kg of buffalo meat will be dried in 7 hrs 44 mins 17 sec. 14 CFM fan is required to flow the required volume of air in the collector.

3.3 Thickness of Base Insulator:

We assume the transmissivity of transparent glass is 0.9 and absorptivity of corrugated GI sheet is 0.9. From Eq. (6), 536.228W amount of heat will be lost by the dryer setup. The overall heat transfer coefficient of absorber surface is 6.758 W/m^2K using Eq. (7) and the heat removal factor (F_r) is considered as 1. The thickness of the insulator was calculated to be 1.182 cm using Eq. (13) [23]. For convenience purpose, 1.5 cm thick polystyrene was used during fabrication.

$$F_r m_a C_p (T_c - T_a) = KA_c \left(\frac{T_c - T_a}{t_b}\right) \quad (13)$$

Where, K is the thermal conductivity of the polystyrene as 0.047 W/mK and t_b is the thickness of insulation.

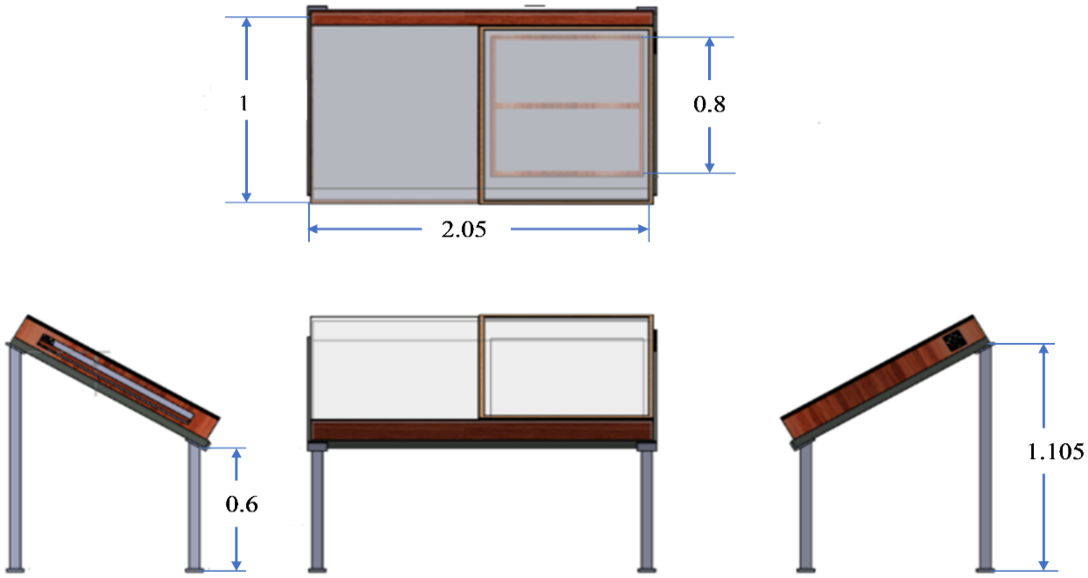


Figure 3: Design drawing (All dimensions are in meters)

Fig. 3 represents the design of the whole dryer setup which was done using Solidworks. Two major parts are: the dryer tray and stand. The overall length and width of the collector tray is 2 m x 1 m. The collector consists of a rectangular inlet of 0.8 m x 0.12 m and a circular outlet of diameter which holds a fan.

4. Fabrication and Experimental Setup:

The fabrication process of the dryer involved the utilization of various materials, namely plywood, polystyrene, and glass. The construction procedure encompassed riveting using nails as fasteners and incorporating glue was deemed necessary. A wooden ply with a thickness of 12 mm was procured and marked accordingly based on the cutting requirements. Subsequently, the marked-out sections were carefully cut out, and the surfaces of the cut pieces were meticulously smoothened. These cut-out sections were then fixed and secured using a combination of glue and nails. To fulfill the insulation prerequisites, polystyrene was affixed inside the nailed box using glue. Then V-corrugated galvanized iron sheets were nailed above the fixed polystyrene within both the primary and secondary collectors to facilitate absorption and total internal reflection of solar radiation. The insulating setup and iron sheet installation are shown in Fig. 4(a) and (b). The collector was painted black to ensure optimal energy absorption in the form of heat. Rectangular slots were then cut out on one side of the dryer box to serve as inlets, while on the opposite side, a hole was carved out to accommodate the exhaust, with the dimensions matching those of the fan. The drying tray was constructed using a combination of wood and aluminum screens. Glazing surfaces were employed to cover both the primary and secondary collectors. The glazing surfaces were affixed onto the upper casing using silicone, and all surfaces were meticulously cleaned.

Table 1: Specification of fabricated parts/components

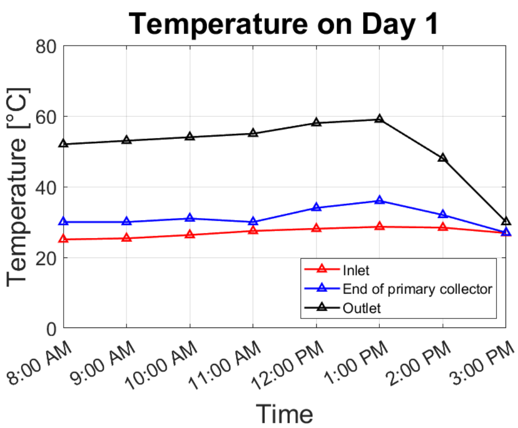
S. No.	Descriptions	Specifications
1	Capacity of dryer	4 kg
2	Dimension of the collector box	2.05 m × 1 m
3	Collector plate area	2 m × 1 m
4	The inlet of the collector	80 cm × 12 cm
5	The thickness of aluminium plate at the side wall	1.2 mm
6	Absorber surface	V- corrugated, GI sheet
7	Insulation thickness	1.5 cm
8	Inclination dryer	30 °
9	Number of trays	1
10	Dimension of trays	80 cm × 80 cm
11	Thickness of glazing surface	4 mm
12	Specification of fan	14 cfm, 6V, 1 Nos
13	Size of fan	90 mm × 90 mm × 25 mm

Figure 4: (a) Insulation setup (b) Installation of absorber and side wall (c) Setup with raw meat kept for drying

Figure 4 (c) shows that 4 kg of buffalo meat in the form of long straps were placed in the drying chamber. The temperature, solar irradiance, humidity at the collector and moisture content of the meat were measured at equal intervals of 1 hr during the drying process. The dryer was placed on the rooftop facing south at 30° inclination.

5. Results:

The temperature of the dryer as inlet, end of the primary collector and outlet were measured throughout the day in the course of two days and plotted as shown in Fig. 5.



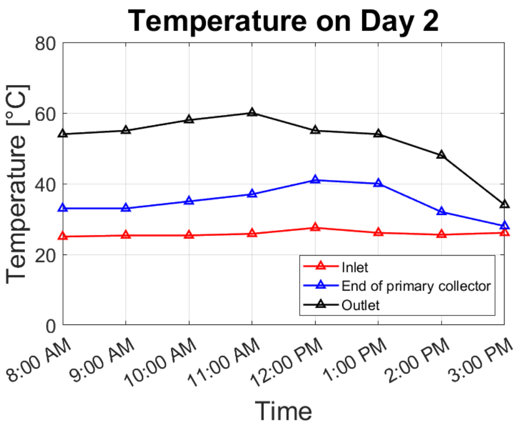


Figure 5: Temperature variation with time

On day one, the maximum and minimum temperature at the outlet of the dryer was 59°C and 30°C respectively, at the end of primary collector was 36°C and 27°C respectively and at the inlet was 28.6°C and 25.08°C. On day two, the maximum and minimum temperature at the outlet of dryer was 60°C and 34°C respectively, and at the end of the primary collector the temperature was at a maximum of 41°C and minimum of 28°C and the inlet was 27.51°C and 25.03°C respectively.

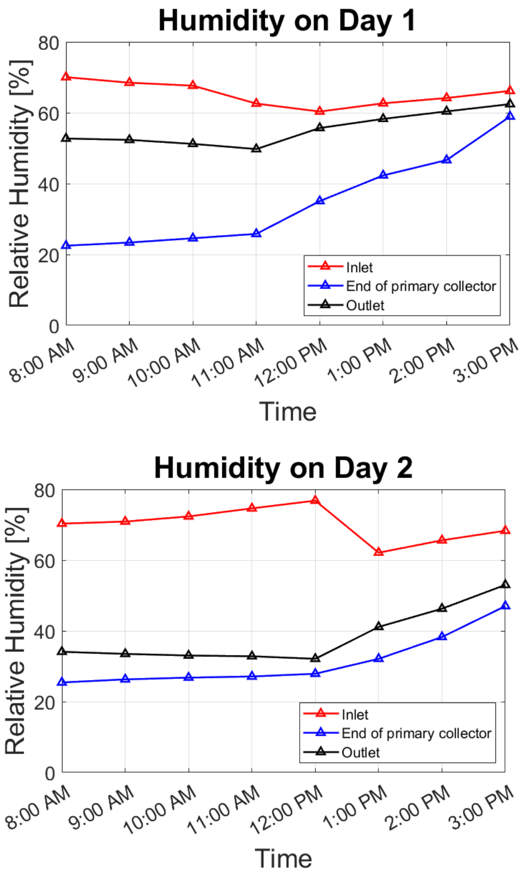
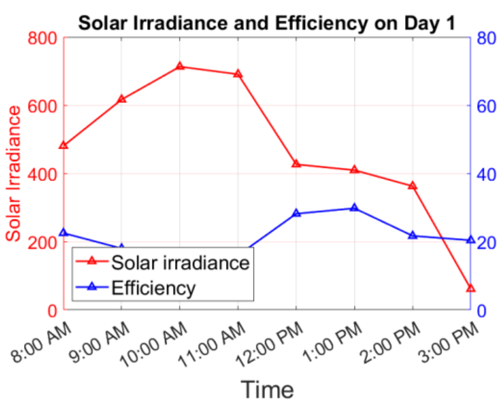


Figure 6: Variation of air humidity during the testing period

Meanwhile, the humidity for each location is measured per hour for both days represented in Fig. 6. Taking the experimental zero time starting from 8:00 AM and the end time as 3:00 PM, the curve for humidity seemed to be influenced by the intensity of solar irradiance. When the air flows in the secondary collector, it carries the moisture of the meat so the humidity at the outlet of the dryer increases as compared to the primary collector.



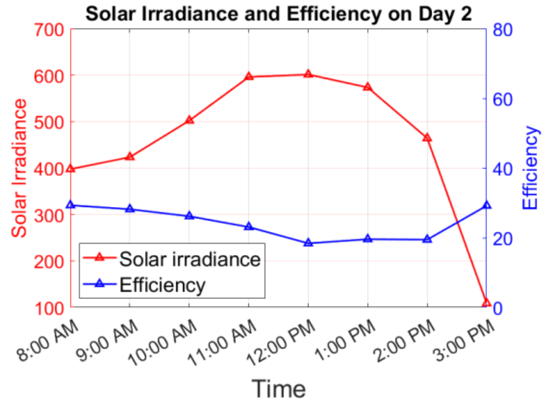


Figure 7: Variation of solar radiation, and efficiency

The efficiency was calculated from Eq. (11) as per design and plotted as shown in Fig. 7. From the relation, the efficiency and solar irradiance had some inverse effects but the influence of useful heat (Q) has also significance on the efficiency.

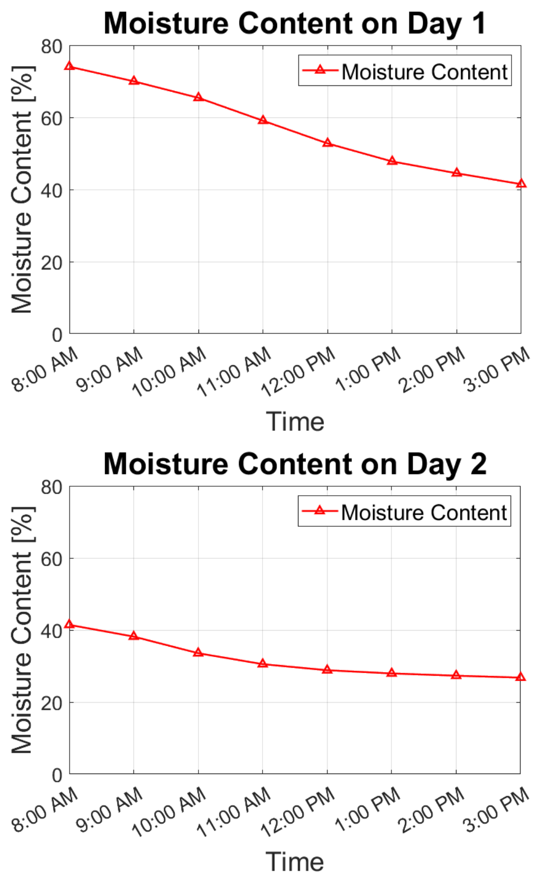


Figure 8: Moisture content with time at design load

The weight of the buffalo meat was continuously decreased due to the moisture loss of meat. The plot of moisture content during the course of two days is illustrates in Fig. 8. From the experiment, the total time required for the reduction of moisture content from 74.04% to 26.78% was found to be 14 hrs. Out of which the contribution of day one was from 74.04% to 41.46% and of the day was from 41.42% to 26.78%. In the transition of both days, 0.04% moisture was removed although it was wrapped within a polyethylene bag.

Figure 9: Dried meats after the drying process

The secondary collector with the final dried meat after the experiment is shown in Fig. 9

6. Conclusion:

In conclusion, the complete methodology and design calculations were presented for a mixed-mode solar dryer by considering the subtropical climate of eastern Nepal. The test subject of 4 kg buffalo meat required a total of 14 hrs for reducing the total moisture to 26.78% of the weight. Meanwhile, from the design it was meant to be 23.2%, which was pretty close but the drying time from the design calculations was 7 hrs 44 mins. This deviation from design and experiment can be justified by the assumption of solar irradiance to be taken as constant throughout the day, but this is not the case in a testing environment. For the design load experiment, the variation of temperatures at the end of the primary collector and outlet of the dryer was found to be higher than the ambient temperature during the evaluation period. Solar dryers can come in handy for the mass production of dried buffalo meat in rural and urban areas of Nepal for business and household purposes. The performance of the designed forced convention mixed mode solar tunnel dryer can still be improved, especially in the aspect of reducing the drying time, and storage of heat energy within the system.

References:

[1] I. V. Thiagarajan, "Combined microwave-convection drying and textural characteristics of beef jerky," 2008.

[2] G. Kandeepan, S. Biswas, and R. Rajkumar, "Buffalo as a potential food animal," International Journal of Livestock Production, vol. 1, no. 1, pp. 001-005, 2009.

[3] R. R. Boyer and K. Huff, "Using dehydration to preserve fruits, vegetables, and meats," 2019.

[4] B. Norton, "Characteristics of Different Systems for the Solar Drying of Crops," in Solar Drying Technology: Concept, Design, Testing, Modeling, Economics, and Environment, O. Prakash and A. Kumar Eds. Singapore: Springer Singapore, 2017, pp. 69-88.

[5] M. G. Green and D. Schwarz, "Solar drying technology for food preservation," GTZ publication Eschborn, Germany, 2001.

[6] M. Sevda and N. Rathore, "Studies on semi-cylindrical solar tunnel dryer for drying di-basic calcium phosphate," Agricultural Engineering International: CIGR Journal, 2007.

[7] F. N. Engmann, W. O. Ellis, V. P. Dzogbefia, M. Yong-Kun, E. Abano, and J. Owusu, "A comparative study of three drying methods for preservation of the giant African snail (Achatina achatina) meat," 2012.

[8] J. Banout, "Solar Drying Systems," in Solar Drying Technology: Concept, Design, Testing, Modeling, Economics, and Environment, O. Prakash and A. Kumar Eds. Singapore: Springer Singapore, 2017, pp. 39-67.

[9] F. Forson, M. Nazha, F. Akuffo, and H. Rajakaruna, "Design of mixed-mode natural convection solar crop dryers: Application of principles and rules of thumb," Renewable energy, vol. 32, no. 14, pp. 2306-2319, 2007.

[10] B. Bala and M. Mondol, "Experimental investigation on solar drying of fish using solar tunnel dryer," Drying technology, vol. 19, no. 2, pp. 427-436, 2001.

[11] P. Singh, V. Shrivastava, and A. Kumar, "Recent developments in greenhouse solar drying: A review," Renewable and Sustainable Energy Reviews, vol. 82, pp. 3250-3262, 2018.

[12] K. T. Zar, "Design Analysis of Moisture Content for Potato Slices in Solar Dryer," Design Analysis of Moisture Content for Potato Slices in Solar Dryer, vol. 18, no. 1, pp. 10-10, 2018.

[13] E. Ayua, V. Mugalavai, J. Simon, S. Weller, P. Obura, and N. Nyabinda, "Comparison of a mixed modes solar dryer to a direct mode solar dryer for African indigenous vegetable and chili processing," Journal of Food Processing and Preservation, vol. 41, no. 6, p. e13216, 2017.

[14] D. Lakshmi, P. Muthukumar, A. Layek, and P. K. Nayak, "Performance analyses of mixed mode forced convection solar dryer for drying of stevia leaves," Solar Energy, vol. 188, pp. 507-518, 2019.

[15] W. Jangsawang, "Meat products drying with a compact solar cabinet dryer," Energy Procedia, vol. 138, pp. 1048-1054, 2017.

[16] S. Ghimire, "Recipe optimization of buffalo meatball," 2018. B.

[17] Naveena and M. Kiran, "Buffalo meat quality, composition, and processing characteristics: Contribution to the global economy and nutritional security," Animal frontiers, vol. 4, no. 4, pp. 18-24, 2014.

[18] A. K. Rai, "Microbiology of traditional meat products of Sikkim and Kumaun Himalaya," Kumaun Univeristy, 2008.

[19] A. Lingayat, V. Chandramohan, and V. Raju, "Design, development and performance of indirect type solar dryer for banana drying," Energy Procedia, vol. 109, pp. 409-416, 2017.

[20] K. R. Adhikari, S. Gurung, and B. K. Bhattarai, "Solar energy potential in Nepal and global context," Journal of the Institute of Engineering, vol. 9, no. 1, pp. 95-106, 2013.

[21] E. Akoy, M. A. Ismail, E.-F. A. Ahmed, and W. Luecke, "Design and construction of a solar dryer for mango slices," Proceedings of International Research on Food Security, Natural Resource Management and Rural Development-Tropentag. University of Bonn, Bonn, Germany, 2006.

[22] I. Hartley, "Wood: Moisture content, hygroscopicity, and sorption," Encyclopedia of Materials: Science and Technology, pp. 9668-9673, 2001.

[23] C. Rojas, M. Cea, A. Iriarte, G. Valdés, R. Navia, and J. P. Cárdenas-R, "Thermal insulation materials based on agricultural residual wheat straw and corn husk biomass, for application in sustainable buildings," Sustainable Materials and Technologies, vol. 20, p. e00102, 2019.