ENERGY AND EXERGY ANALYSIS OF SOLAR-ELECTRICAL HYBRID DRYER

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Drying is one of the ancient methods of food preservation. It is one of the unit operations in the postharvest phase. Drying is the removal of water from a solid, semi-solid or liquid to a predetermined level by virtue of simultaneous heat and mass transfer. Drying is preferably done to increase the storage life of food. Drying reduces the water activity of food which in turn helps to arrest or delay the microbial activity and chemical reactions thus dried food can be stored for longer time. Drying also enhances the product flavours and texture to provide definite sensory properties. Dried foods are more suitable for handling and reduces the cost of packaging, transportation and storage. Dried foods are delicious, nutritious, lightweight and easy-to-store and use (Ahmed et al. 2013).

Drying operations use a lot of energy, accounting for 7–15% of the sector's overall energy consumption in some nations and possibly as much as 33%, and they have only 25–50% thermal efficiency (Dincer and Ezzat 2018). There are numerous methods of drying. The predominant food drying methods are open sun drying and shade drying. Other improved conventional methods are hot air drying and cabinet or oven drying. Non-conventional methods of drying include solar drying, microwave drying, infra-red drying, freeze drying, etc.

The traditional methods of drying such as open sun drying have disadvantages like longer drying period, contamination and adversely affected by weather conditions. Sun drying is being the most widely practiced method throughout the world for drying agricultural commodities. Sun drying is just spreading things in out-doors in the open sun and letting them dry. It is one of the cheapest methods drying and energy is freely available, renewable and abundant. But it takes quite a few days to dry foods in out-doors. As the weather conditions is not controllable, sun drying can be uncertain. And also, direct exposure of the food material to unhygienic open conditions may cause dust, excreta, pests, insects and microbial infestations and yield inferior quality product.

Fish or shrimp is being the most cost-effective animal protein source and because of its high perishability, and sun drying were used to dry fish and to preserve the same (Paul et al. 2018). To overcome the drawbacks of sun drying, mechanical dryers with electric heating system are generally used. But this involve running costs due to electricity consumption and are not recommended due to exploitation of non-renewable sources of energy and leaving carbon footprint. Recent efforts are made to improve the open sun drying and has been led to adoption of solar drying method which is one of the best solutions to avoid the disadvantages of open sun drying.

Solar energy is freely available abundantly and can be easily harnessed. Solar energy is radiant energy from sun in the form of light and heat that can be collected using a range of technologies to generate electricity and thermal energy. Solar energy can be effectively utilized for drying purpose in an efficient way using solar thermal collectors.

Solar drying involves a design to capture and magnify the heat from the sun, as well as to help protect the material from infestation of dusts, insects, pests and other foreign bodies. Quicker drying process reduce the menaces of spoilage or microbial attack. Even though farmers were using sun drying for several centuries, but recently, solar drying has been widely accepted over open sun drying, as it is more effective. Solar dryers use solar energy which is renewable and freely available and therefore the effective utilisation of solar energy in drying process makes the dryer operated at low cost with maximum energy efficiency. Solar dryers are classified as direct dryers, indirect dryers, greenhouse solar dryers, hybrid solar dryers, solar dryers with thermal energy storage systems etc. Among all, solar drying is most effective for fish or shrimp drying as it is using renewable energy for drying. And also, many studies have proven that solar drying is a method of food preservation as the food is dried under controlled conditions and fully protected from infestation of rain, dust, insects, pests and animals during drying.

Solar energy is used either as the sole heating source or as a supplementary heating source. Solar dryers use atmospheric air to get heated by the help of solar thermal energy collectors. The hot air flow can be made either by forced or natural convection. The energy of from solar radiations used to heat the air that flows into the dryer through the material in the dryer. As the air is heated up, its humidity decreases and is capable of holding more moisture. The drying will happen by the passage of the hot air through the food kept in the chamber or by directly exposing the food to solar radiation in the thermal collectors, or a combination of both. The heat transfer to the moist food from hot air will occur by convection and conduction which is at temperatures above that of the food, or by radiation from the sun and to some extent from the surrounding hot surfaces, or by conduction from heated surfaces in contact with the food.

Solar dryer can perform drying for food preservation only during sunny days, and hence the drying efficiency depends largely on climatic conditions and the season (Nukulwar and Tungikar 2022). Hybrid solar dryers are more reliable as there is a back-up system to provide heating in it. Solar-electrical hybrid dryer is more trustworthy as auxiliary system is electrical heating coil. Hybrid solar dryer would lessen the drying costs (in comparison with the elecrical dryer's costs) and also there is a possibility to improve the quality of the dried food by controlling the drying condition in solar hybrid dryer (Ferreira et al. 2007).

Solar hybrid dryers use different energy sources for auxiliary or back-up heating. Studies are already done on the solar hybrid dryers with solar water heaters and electric water heating coil (Amer et al. 2010) biomass back-up (Dhanuskodi et al. 2014; Sonthikun et al. 2016), sensible heat storage using water heaters and LPG back-up (Murali et al. 2021), biogas powered air heaters (Rupnar et al. 2020), steam based solar hybrid dryers (Nukulwar and Tungikar, 2020), ohmic heating (Richa et al. 2021) and black pebble-based sensible heat storage (Andharia et al. 2023) based solar dryers.

Design and working of solar-electrical hybrid dryer

The solar-electrical hybrid dryer (SEHD) comprises a solar air collector, a drying cabinet, blowers and fans, an electric heating coil, and a temperature sensor. The solar air collector is connected to the cabinet of the dryer. The cabinet is fabricated with a stainless-steel box with insulated PUF (polyurethane foam) walls and five trays, each capable of holding 2 kg of fish. T h e drying trays of food-grade quality (ss 304) was used to hold the materials in the cabinet and make it easier to (un)load or shift the trays. The door of the dryer was appropriately sealed to stop any heat loss and for accessing the products inside the chamber. The collector's hot air will enter the bottom dryer cabinet. The fluctuation in the drying air temperature depending on the incident solar radiation at the flat-plate collector, was regulated by a supplementary heat source. The blower supplies the air through the heating coil placed inside the drying chamber's double frame structure, and heated air will enter the drying chamber through the perforations made at the side bottom of the cabinet beneath the trays. Then the heated air will pass through the material over the trays removing the moisture from the material and throwing it out with the help of exhaust fans. If the dryer temperature was not attained, the heating coil will be heated up to attain the desired temperature in the cabinet, which is controlled thermostatically.

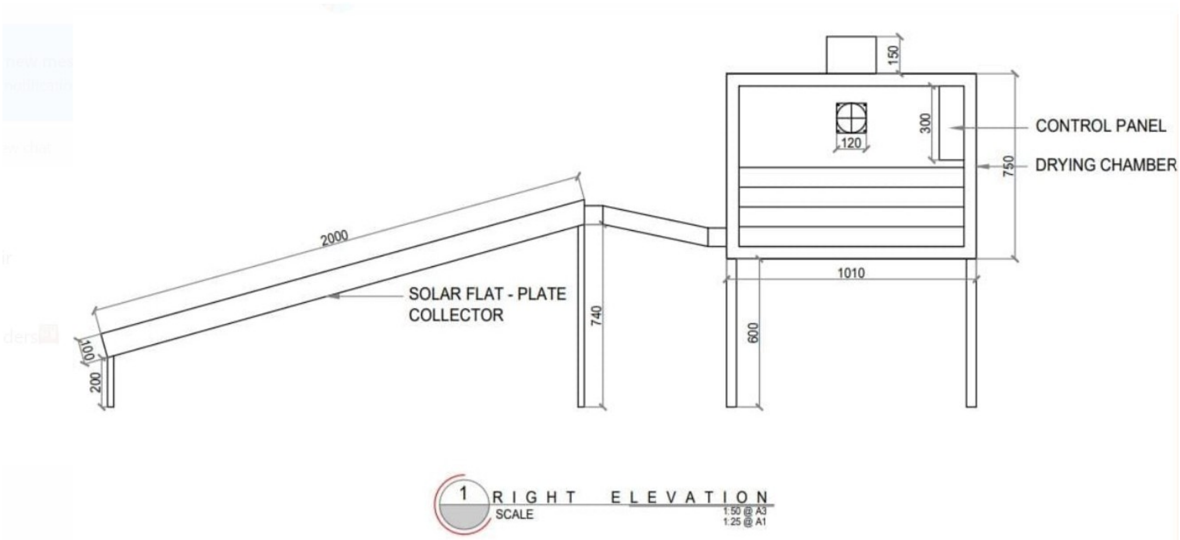
Energy analysis

Initially, the parameters such as the initial moisture content, final moisture content and total mass of the fish to be dried was estimated to calculate the quantity of moisture to be removed during drying (M_w, kg).

$$\boxed{M_w = M \times \frac{M_i - M_f}{100 - M_f}} \quad (1)$$

The heat energy required to dry the material is calculated by taking into account of weight of material to be dried (kg), quantity of moisture to be evaporated (kg), specific heat of water (kJ/kg℃), latent heat of vaporization (kJ/kg) and the difference in temperature between ambient and drying conditions.

$$\boxed{Q = M} C_{pw} \boxed{\Delta T +} M_w \lambda \quad (2)$$



Schematic Diagram of the solar-electrical hybrid dryer

The drying efficiency of SEHD was calculated by the amount of energy required to remove the moisture from the material to the energy supplied (by the solar collector electrical coil). The sensible and latent heat is the total energy required to dry the material. The energy required to raise the temperature of the food to a dryer temperature is called sensible heat. The latent heat of vaporization is the energy required to vaporize at drying temperature (Leon et al. 2002). The energy absorbed by the solar air collector and energy utilized by the heating coil, exhaust fans, blowers, etc., is the energy supplied. The drying effieciency was calculated using the following equation (Vieira et al. 2007).

$$The\ Drying\ Efficiency = \frac{(Energy\ required\ to\ remove\ moisture)}{(Energy\ supplied\ by\ heating\ coil + Energy\ supplied\ by\ solar\ collector)} \quad (3)$$

The solar-electrical hybrid dryer was having a drying efficiency of 28.65%, with an average incident radiation of 710 W/m^2. The major part (65%) of thermal energy required for shrimp drying was supplied by solar radiations, and the remaining part (45%) was provided by the electrical heating coil as an auxiliary system when operated in hybrid mode (Cisni et al. 2023).

Exergy analysis

Exergy is the "available energy" or "usable energy" which represents the portion of energy that can be converted into useful work, such as mechanical work or electrical work, under ideal conditions. The remaining energy that cannot be converted into useful work is considered wasted energy. The concept of exergy analysis, which assesses the thermal efficiency of a system, is based on the fundamental principles of the second law of thermodynamics. The concept of exergy is applicable to analysis, design and optimization of energy conversion processes and systems. The exergy output is inherently lower than the exergy input due to the presence of irreversibilities and this loss is directly proportional to the entropy formation within the process (Mugi et al. 2021). Overall, exergy provides a valuable tool for assessing the efficiency and sustainability of energy systems by considering not only the quantity of energy but also its quality and the potential for useful work extraction.

This approach considers the transfer of mass, heat, and work within the system to evaluate its overall exergy in the process and calculated by the following formulas (Kumar et al. 2023).

$$Ex = \dot{m}C_p\left[(T - T_a) - T_a \ln\frac{T}{T_a}\right] \tag{4}$$

$$Ex_{loss} = Ex_i - Ex_o \tag{5}$$

$$\eta_{Ex} = \frac{Ex_o}{Ex_i} \tag{6}$$

The exergy efficiency of the drying chamber of SEHD was found to be 28.57%, indicating the portion of available exergy that is effectively utilized (Cisni et al. 2023). Ndukwu et al. (2022), also reported a range of exergy efficiency values from 19.09% to 52%. The exergy loss associated with the drying chamber of SEHD was measured as 0.70, indicating the magnitude of exergy dissipation during the drying process. On the other hand, the exergy efficiency of the solar air collector was found to be 62.50%, demonstrating the effectiveness of energy conversion from solar radiation to usable exergy. The exergy loss attributed to the solar air collector was calculated to be 0.34, representing the extent of exergy degradation within the collector (Cisni et al. 2023).

Fig. 2. Shrimp before and after drying in SEHD

In the same way in the study conducted by Mugi et al. (2021), exergy analysis was performed separately for both the solar air collector and the drying chamber. The low exergy efficiency of the drying chamber suggests potential areas for improvement, such as enhancing insulation, optimizing air flow pattern, or implementing more efficient heat transfer mechanisms. Similarly, the exergy efficiency of the solar collector in the hybrid dryer was found to be 62.43%. The high exergy efficiency of the solar collector highlights the effectiveness of harnessing solar energy for drying applications due to its advanced design, optimized orientation, and efficient heat transfer mechanisms. The associated exergy loss with the solar collector was measured as 0.34, representing the energy lost during the conversion process. This loss can be attributed to factors such as thermal losses, optical inefficiencies, and the unavoidable limitations of energy conversion technologies.

Abbreviations

M	Weight of shrimp to be dried (kg)
M_w	Amount of water to be removed (kg)
M_i	Initial moisture content (% w. b.)
M_f	Final moisture content (% w. b.)
Q	Heat energy requirement (kJ)
C_p	Specific heat of air (kJ/kg℃)
C_{pw}	Specific heat of water (kJ/kg℃)
ΔT	Temperature change between ambient and drying conditions (℃)
λ	Latent heat of vaporisation (kJ\kg)
ṁ	Mass flow rate of air (kg/s)
Ex	Exergy
Ex_i	Exergy Input
Ex_o	Exergy Output
Ex_{loss}	Exergy Loss
η_{Ex}	Exergy Efficiency
T_a	Atmospheric Temperature

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