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Evaluation Of The Efficiency Of Exergy Losses In Low-Potential Dryers

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Abstract: This scientific study provides a comprehensive investigation of the exergy losses that occur during the operation of low-potential solar and air-based drying systems. It covers the nature and primary sources of these losses, as well as the theoretical evaluation methods. Low-potential dryers operate at relatively low temperatures in the range of 40–65 °C. While these low-temperature processes may be highly energy efficient, they often result in low exergy efficiency. Therefore, identifying and reducing exergy losses in drying systems can significantly enhance the scientific and practical relevance of the process. A theoretical model is used to present the exergy potential of solar radiation, the exergy of the air streams entering and exiting the dryer, the binding energy of moisture in the dried product and the general exergy balance equation. When evaluating exergy losses, the main variables considered are the maximum useful utilisation level of solar radiation, the optical coefficients of the absorber surface, the air velocity inside the drying chamber, the moisture transfer rate and the heat transfer coefficients. Additionally, the structural dimensions of the dryer, the material of the transparent cover, the ventilation regime and the humidity and temperature of the air mixture are shown to have a significant impact on exergy efficiency on a scientific basis.

Keywords: Solar dryer, solar collector, thermal stability, aerodynamic cooling, thermal insulation, convective–contact drying, black stone heat accumulator, polyethylene cover, ultraviolet energy, renewable energy sources.

INTRODUCTION:

In recent years, demand for low-energy drying technologies has increased sharply, driven by the need to improve the storage and processing of agricultural products and enhance export potential. Low-potential solar-based dryers (LPSDs) play a significant role in this process as they operate at relatively low temperatures of 40÷65 °C, making them environmentally friendly, economically viable and energy efficient. However, evaluating such dryers solely from an energy perspective does not accurately reflect their performance. This is because the conversion of energy into useful work is limited in low-temperature processes, while exergy losses increase significantly. Therefore, a thorough theoretical investigation of exergy losses in drying systems is an important scientific task [1-4].

Exergy represents the maximum useful work that a system can perform as it approaches equilibrium with the environment, and thus characterises the quality of a thermodynamic process. Although energy is conserved, exergy can be destroyed; such losses are associated with thermodynamic irreversibilities within the system, entropy generation and improper control of heat and mass transfer processes. In low-potential dryers, the main sources of exergy losses include the dryer’s structural design, airflow mechanisms, optical processes on the absorber surface, moisture removal dynamics and temperature gradients during heat exchange. Conventional convective or radiative solar fruit dryers typically only operate efficiently under sunny conditions. However, due to the inadequate development and insulation of their thermal energy storage components, a large proportion of the accumulated heat energy is lost. Consequently, the drying process of fruits and plant materials is prolonged, resulting in a deterioration in product quality.

The drying process inherently requires energy to remove bound moisture from the product. The magnitude of this energy demand depends directly on the thermodynamic state of the system, the properties of the air–vapour mixture, temperature gradients and the aerodynamic conditions within the drying chamber. In particular, at low temperatures, the rate of moisture evaporation decreases while resistance to heat and mass transfer in airflow increases, intensifying entropy generation. Consequently, significant exergy losses occur within the drying system. Conducting exergy analysis in low-potential dryers therefore enables useful energy potential losses to be identified at each stage of the process and supports their minimisation [5].

Accordingly, numerous scientific studies have recently focused on improving the energy performance and optimising the structural design of solar dryers. Analysis of the scientific literature indicates that improving the energy efficiency of solar dryers requires attention to be given primarily to improved thermal insulation, aerodynamic temperature control, optimisation of the thermophysical properties of thermal storage modules and implementation of automatic control systems that account for variability in solar radiation.

LITERATURE SURVEY

The use of environmentally friendly, low-cost solar energy for drying agricultural products has become increasingly widespread. Low-potential solar dryers typically operate within a temperature range of 30÷60 °C. However, due to the low temperature of the energy source, the exergy efficiency of these systems is inherently limited. Under these conditions, heat transfer coefficients are relatively low while entropy generation is high.

Mukanema and Simate presented an energy, exergy and economic analysis of a mixed-mode natural convection solar tunnel dryer designed for drying banana slices. Separate energy and exergy balances were established for the solar collector, drying chamber and chimney, and the time-dependent variations in the efficiencies of each component were evaluated. The results suggest that such drying systems can be economically viable despite their limited exergy efficiency when low-potential and natural-convection operating modes are selected [6].

Abdurakhmanov, Takhirov and Rejabov analysed the energy efficiency of an indirect-type solar dryer using classical heat transfer and thermal engineering methods. The dryer's design incorporates an air-heating unit, trays for the drying material and a natural convection airflow mechanism. The experimental results demonstrate the distribution of air temperature and temperature variation across the different tray levels inside the drying chamber. Consequently, the proposed system achieved an energy efficiency of 75÷85% [7].

Meanwhile, Midilli and Küçük investigated the solar drying process of pistachio samples by comparing several classical thin-layer drying models, including the Newton, Page, and Henderson–Pabis models. Based on this comparative analysis, they proposed a new combined empirical model. This model integrates an exponential decay term with a linear time component, enabling drying curves to be represented with a high degree of accuracy. Statistical indicators such as the coefficient of determination (R^2), chi-squared (χ^2) and root mean square error (RMSE) confirm the superiority of this model over other empirical formulations. Consequently, the 'Midilli–Küçük equation has been widely adopted in subsequent studies as the standard model for describing drying kinetics, particularly for low-potential solar drying systems. Among other authors, Mukanema and Simate conducted integrated energy, exergy and economic analyses of mixed-mode natural-convection tunnel dryers. Their studies demonstrate that energy–exergy–economic modelling should be treated as a unified framework for the evaluation and design of drying systems. This approach involves a mathematical model that considers not only heat and mass transfer parameters, but also the economic performance of the drying system [1].

Qodirov Jobir Ruzimamatovich (Bukhara) presented a solar dryer with indirect heating and natural convection airflow, designed for drying apricots. The drying duration was eight days for fresh apricots and five days for dried apricot halves. The dryer's solar collector generated 3313.23 kJ of thermal energy per day, corresponding to a saving of 0.923 kWh of electrical energy or 0.34 kg of conventional fuel equivalent. Apricots with an initial mass of 50 kg and an initial moisture content of 90% required 80 hours to reduce the final moisture content to 20% under open-air drying conditions; the indirect solar dryer achieved the same result in 60 hours [2]. Consequently, the system's productivity with respect to the dried product increased by 25%, while the cost of drying apricots decreased by a factor of 1.21–1.33.

METHODS

This research aims to improve the design of a cabinet-type solar dryer, enhancing its energy efficiency and overall performance. An upgraded solar collector was used to experimentally investigate the heat transfer characteristics, aerodynamic behaviour and thermal energy storage performance of the fruit drying process. The experimental data obtained provide a basis for analysing the efficiency of thermal energy utilisation in the system and serve as a foundation for further constructive optimisation stages [8-9].

The overall exergy balance for the drying system can be expressed as follows:

$$E_{pr.} = E_{usef.} + E_{loss.} \quad (1)$$

Exergy is defined as the maximum amount of useful work that can be extracted from a system when it reaches equilibrium with its surroundings. Low-potential dryers operate at relatively low temperatures (25–60 °C) and, in some cases, under fluctuating energy input conditions. As a result, such systems:

cannot utilise the available thermal energy fully;

- experience irreversible losses due to friction, convection, heat transfer and mass transfer processes;

They also exhibit a reduction in exergy caused by an increase in air entropy during the drying process.

Under these conditions, a significant proportion of the supplied energy loses its ability to perform useful work, resulting in low exergy efficiency.

The exergy of the system can be determined as follows:

$$E_x = Q(1 - T_0/T) \quad (2)$$

Q is the amount of heat supplied, T is the air temperature inside the dryer and T_0 is the ambient temperature. In low-potential dryers, the exergy is relatively low due to the small value of T_0, and losses can be significant.

Exergy efficiency:

$$\eta_{ex} = E_{usef}/E_{pr.} \cdot 100\% \quad (3)$$

In low-potential drying systems, this indicator usually falls within the range of 4–18%. Low-potential drying systems offer significant advantages in terms of reducing energy consumption and promoting the use of renewable energy sources. However, from an exergy analysis standpoint, they have certain limitations since low operating temperatures, heat losses and increased entropy generation during the process substantially reduce exergy. Identifying and classifying exergy losses according to their sources, as well as developing theoretical approaches to reduce them, can increase the overall efficiency of low-potential dryers by 15–30%. Therefore, exergy analysis is an essential theoretical tool for the scientific development of low-potential drying technologies.

When conducting such an analysis, the exergy potential of solar radiation, the degree of order of the energy transmitted through the absorber, the proportion of thermal energy in the air stream that is actually useful, the thermodynamic binding characteristics of the moisture in the dried product and the variations in entropy within the drying chamber are all explicitly taken into account [10-13]. This provides a solid scientific basis for optimising the structural parameters of low-potential drying systems, selecting appropriate construction materials, enhancing thermal insulation levels, controlling air exchange and improving absorber surface optical properties.

The relevance of the present study is determined by the following factors:

- the growing demand for energy-efficient drying technologies;
- the high level of exergy losses inherent in low-potential dryers;
- the necessity for the scientific justification of dryer design optimisation;
- the ability of exergy analysis to accurately assess

process quality.

Figure 1. Insulation of the base part.

Figure 2. External view of the collector.

Taking the above considerations into account, this study aims to provide a scientific basis for understanding the mechanisms of exergy losses in low-potential dryers, how to quantify them, what causes them, and how to reduce them. The research results have practical significance for improving the energy and exergy efficiency of drying systems, enhancing dryer design and enabling more effective utilisation of solar energy (Figures 1 and 2).

To increase the system's energy and exergy performance, the bottom part and side walls of the dryer were thermally insulated. To minimise radiative losses from the absorber, the upper part of the transparent cover was properly sealed and protected. The high moisture content of apricots, which can reach 80–86%, together with their cellular structure, makes the drying process a complex heat and mass transfer phenomenon. During the diffusion of moisture from the interior of the product to the surface and throughout the evaporation process, the following factors directly influence exergy losses:

- internal diffusion resistance;

- external convective resistance;

- temperature gradient;

- variation in air humidity.

These interacting factors intensify thermodynamic irreversibilities within the drying chamber, playing a decisive role in determining the exergy efficiency of low-potential solar drying systems overall.

Due to the high level of entropy generation in these processes, the exergy efficiency of apricot drying in low-potential dryers may range from 10% to 30%. Unlike energy, exergy is not conserved; a certain portion of it is destroyed during the process as a result of entropy production. Several coupled phenomena can be observed in the apricot drying process, including air heating, moisture diffusion within the product's internal structure, surface evaporation, heat conduction and convective heat and mass transfer. Each of these processes reduces the available exergy.

Although low-potential dryers generally exhibit relatively high energy efficiency, their exergy efficiency is considerably lower since the exergy potential decreases as the temperature falls. The high initial moisture content of apricots, which can reach 80÷86%, together with their cellular structure, makes the drying process a complex heat and mass transfer phenomenon. During the diffusion of moisture from the interior of the product to the surface and throughout the evaporation process, factors such as internal diffusion resistance, external convective resistance, temperature gradients and variations in air humidity directly impact exergy losses. Due to the high entropy generation associated with these mechanisms, the exergy efficiency of apricot drying in low-potential dryers is typically in the range of 10÷30%.

The research results indicate that enhancing the thermal energy storage capacity of solar collectors can improve the overall energy efficiency of solar dryers by 20÷25% [3, 4]. At the same time, selecting the right insulation components and heat storage/transfer materials for the collector — such as black stones, polyethylene layers or metal plates — has a significant influence on the heat loss coefficient. Consequently, high-efficiency collector systems enable environmentally friendly, hygienic and high-quality drying of fruit and plant materials.

Figure 3. Drying of apricot product.

Drying fruits in open areas using natural solar radiation requires a very long time. For example, grapes require approximately 30÷35 days, apricots 8÷11 days, and melons 5÷6 days to dry completely [5,6]. These durations are about three to four times longer than the operating time required by currently available solar dryers, highlighting the low efficiency of open-air drying compared to controlled heliodrying systems.

Table 1

Indicators of external and internal parameters during drying of apricot products.

Time (hours)	**Apricot weight** (kg)	**Solar radiation** W/m^2	**Outdoor temperature** °C	**Temperature inside the cabinet** **°C**	**Humidity inside the cabinet** %
8:00	75	588	29	33	18
10:00	71	778	34	45	24
12:00	67	936	37	58	22
14:00	62	978	38	64	18
16:00	59	810	36	64	16

According to the experimental results, 75 kg of fresh apricots lost around 82% of their initial moisture content over a 54-hour drying period, yielding 33.3 kg of dried product. The drying process was highly efficient, and the quality of the finished product, particularly in terms of colour, taste and mechanical integrity, was superior to that obtained through natural open-air drying.

RESULTS AND DISCUSSION

The efficiency of a solar collector is defined as the ratio of the useful thermal energy gained to the portion of incident solar radiation received by the collector's absorbing surface. The effective receiving area of the collector corresponds to the surface on which solar radiation has an effective impact. The collector's efficiency depends strongly on its operating conditions and design characteristics. Some of the solar radiation incident on the collector surface is reflected back due to optical losses. By analysing the relationship between incident solar radiation and the radiation power converted into thermal energy at the absorber, total heat losses in the solar collector can be calculated.

$$\sum Q_{loss} = Q_{tr.coat.} + Q_{dust} + Q_{under} + Q_{slot}. \quad (4)$$

During the scientific research, in order to minimize heat losses in the solar collector, the bottom part of the collector (ground side) was thermally insulated to prevent the absorption of thermal energy by the ground. For this purpose, the surface was treated with liquid glass wool and bitumen, allowed to dry, and then covered with reflective foil-faced glass wool. As a result, effective thermal insulation between the collector and the ground was achieved.

Consequently, the amount of heat lost through the bottom of the collector, Q_slot, can be considered to be close to zero, meaning that thermal energy is practically not absorbed by the lower part of the collector. Under this assumption, Equation (4) can be written in the following form:

$$\sum Q_{loss} = Q_{tr.coat.} + Q_{dust} + Q_{slot} \quad (5)$$

From Equation (5), it can be determined that the efficiency of the solar collector increases. To prevent the stones used for thermal energy storage from coming into direct contact with the glass wool insulation at the bottom, wooden slats with a thickness of 6.5 cm were installed in parallel between the stones and the glass wool (Fig. 2). During the drying of apricot products, the collector section was well insulated, which allowed the drying cabinet to be supplied with thermal energy even during the evening hours. As a result, the drying process was continuous and uninterrupted.

Based on the conducted experiments and analyses, it was determined that the improved solar collectors possess several important advantages. In particular:

High efficiency: the thermal energy utilisation coefficient is 70÷80%.

Ease of maintenance: thanks to its simple design, the system requires minimal routine servicing.

Ease of fabrication: all the main components (cabinet, stone heat storage unit, polyethylene cover and ventilation channel) can be assembled in basic conditions.

Use of locally available materials: the system can be constructed using metals, wood and polyethylene materials that are commonly found in households.

It is several times cheaper than conventional electric or gas dryers in terms of economic efficiency.

Long service life: the overall lifetime is 15÷20 years, while the transparent film has an average service life of 7÷8 years.

High thermal stability: the collector maintains a stable and balanced internal temperature.

Climate adaptability: it operates efficiently in hot, dry conditions.

CONCLUSIONS

In low-potential dryers, exergy losses are mainly associated with the use of low-temperature heat sources, intensive heat exchange with the ambient environment, and the irreversibility of heat and mass transfer processes. Based on the research findings and theoretical analysis, the following scientific and practical recommendations are proposed:

1. Implementation of exergy analysis as a primary evaluation criterion

In the design and modernization of low-potential dryers, exergy analysis should be applied mandatorily alongside conventional energy (first-law) analysis. This approach enables an accurate assessment of the actual thermodynamic perfection and performance of the system.

2. Optimization of heat transfer processes

The thermal performance of transparent covers, absorber surfaces, and the drying chamber should be improved to minimize heat losses. Reducing heat losses directly contributes to lowering exergy destruction within the system.

3. Adaptive control of airflow and drying regime

Automatic control of air velocity and temperature (e.g., using sensors and simple microcontrollers) helps maintain the drying process closer to thermodynamic equilibrium and reduces the degree of irreversibility.

In this study, the problem of evaluating exergy losses in low-potential dryers was analyzed from a scientific perspective. The results show that such systems may exhibit acceptable performance in terms of energy efficiency; however, their exergy efficiency often remains low. This behavior is primarily explained by the high irreversibility of heat and mass transfer processes. Exergy analysis reveals that the major losses occur in the solar collector, within the drying chamber, and during heat exchange with the surrounding environment.

Overall, the proposed measures aimed at reducing exergy losses can significantly enhance the scientific and technical level of low-potential dryers, transforming them into efficient and environmentally acceptable technologies for agricultural product drying. If design and control strategies are developed based on exergy criteria, the practical applicability and widespread adoption of this type of dryer are expected to increase substantially.

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