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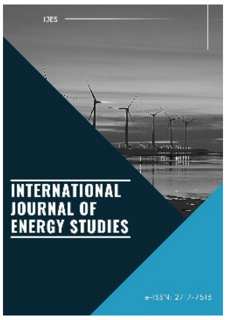

Research Article

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An experimental research on the effect of infrared and carbon fiber film heater integration in heat pump food drying system on drying performance

Ümit İşkan[a], Ahmet Yüksel[b*], Cüneyt Tunçkal[c]

[a]Yalova Vocational School, Electricity and Energy Department, Yalova University, 77200 Yalova, Turkiye, ORCID: 0000-0001-6236-2339

[b]Yalova Vocational School, Electricity and Energy Department, Yalova University, 77200 Yalova, Turkiye, ORCID: 0000-0002-0472-0342

[c]Yalova Vocational School, Electricity and Energy Department, Yalova University, 77200 Yalova, Turkiye, ORCID: 0000-0002-9395-3534

*(*Corresponding Author: ahmet.yuksel@yalova.edu.tr)*

Highlights

- Infrared lamp and carbon fiber film heater were integrated into the heat pump drying system.
- IR and CFH integration was suggested for the HPD system to reach steady state faster.
- 28% time and 25% energy savings could be achieved with the IR and CFH supported HPD system.

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ABSTRACT

In this study, a closed-circuit heat pump food drying system was investigated by integrating a 50 W infrared lamp (IR) and a carbon fiber film heater (CFH) into the cabinet to dry 3 mm thick apple slices at 1 m/s air speed and 40°C temperatures. The study aimed to investigate the differences in drying performance and energy consumption between a typical heat pump drying system (Scenario-I) and an IR and CFH supported heat pump drying system (Scenario-II). The results of the six-hour experiments conducted under laboratory conditions showed that the system reached a steady state 50% faster in Scenario-II and 41 g more moisture was extracted from the products. Furthermore, a 2% decrease in energy consumption and cost caused by the compressor was observed with IR and CFH support. The products that initially weighed 600 g were reduced to 200 g by 28% faster with 25% energy savings in Scenario-II. Finally, it was determined by thermal camera images that the products were dried homogeneously thanks to CFH. Therefore, it has been identified that IR and CFH supported HPD systems are preferable systems in terms of energy saving for low compressor load and fast drying processes.

Keywords: Heat pump drying, Carbon fiber film heater, Infrared, System performance

1. INTRODUCTION

Fresh vegetables and fruits tend to deteriorate after harvesting due to their delicate textures and moisture content. Physical and biochemical deformations that may occur in fresh foods during transportation and storage processes can cause deterioration of product quality and decrease in market value [1]. These negativities, along with the increase in food demand due to population growth, reveal the importance of food storage conditions and durations [2].

One of the most common techniques used for preserving fresh produce is drying, which is the process of releasing and removing moisture from the produce. The most environmentally friendly method known is the traditional drying of products by leaving them in the open air under the sun. However, it is defined that the drying period can last for days depending on the kind of product and its moisture content in this traditional method [3]. For this reason, various technological systems with shorter drying times are used in the food industry compared to natural drying methods. However, energy consumption and greenhouse gas emissions resulting from these systems can lead to threats such as global warming and climate change. In a study conducted by Mohanraj [4], it was specified that the energy consumption resulting from the drying of agricultural products in developed and developing countries constitutes more than 10% of the total energy consumption. Therefore, researchers investigate and develop more efficient, economical, and environmentally friendly alternatives to increase energy savings and sustainability in drying systems [5,6].

Various drying techniques are used in the food industry, such as vacuum drying [7], microwave drying [8], superheated steam drying [9], osmotic drying [10], infrared drying [11], and heat pump drying [12]. Drying method with heat pump drying (HPD) systems is a widely preferred technology for drying foods due to its advantages such as having coefficients of performance (COP) above 1 and providing high efficiency with low energy consumption [13,14]. Basically, HPD systems work on the principle of increasing the temperature with the condenser heat, releasing the moisture in the product content, and removing the moisture transferred to the air with the help of the evaporator [15]. HPD systems can easily adapt to different drying conditions for different products, allowing them to be used for a more flexible product range [16]. Besides, low temperature drying processes can be carried out in these systems to ensure that the color, aroma, flavor, and nutritional components of foods are preserved. Therefore, with the HPD technique, quality products can be obtained in an environmentally friendly manner with less energy consumption and greenhouse gas emissions compared to other drying methods.

There are various studies in the literature on the development of HPD systems and their comparison with other systems. Singh et al. [17], who examined the drying of 2 mm thick banana and potato chips in an HPD system operating in both open and closed cycles, determined the exergy efficiencies of the dryer and evaporator as 33.5% and 52.6%, respectively. Duan et al. [18] compared a new tunnel-type air-source HPD system with the traditional hot air drying method. In the study, drying air temperature and relative humidity were examined at 120 and 130 minutes of drying time and 1.5-3 m/s air flow speeds. The COP value of the tunnel type HPD system was determined as 3.45 and the specific moisture extraction rate was determined as 0.93 kg/kWh, and a significant saving of up to 33% in energy consumption was achieved. Türkdoğan et al. [19] added a 550 W external electric heater to the drying chamber entrance of the HPD system and monitored the power consumption during the drying of eggplant slices. The compressor and external heater in the system could be operated separately or together to provide a constant air temperature of 35°C and suitable drying conditions were provided with varying humidity levels between 20% and 40%. In case of 1530 W active power consumption of HPD system, approximately 1600 VAR reactive power consumption occurred. Mohanraj [4] evaluated the performance of a hybrid HPD system under hot and humid conditions. It was assigned that the COP value of the system varied between 2.31 and 2.77 and the heating capacity of the condenser was between 2900 and 3750 W. Additionally, the specific moisture extraction rate (SMER) was determined as 0.79 kg/kWh. Tunckal et al. [20] used a closed-loop air-source HPD system connected in series to an external condenser circuit for drying banana slices. The results of the study demonstrated that the highest exergy losses occurred in the condenser and compressor with 0.366 and 0.557 kW. Furthermore, it was specified that the total exergy efficiency of the HPD system varied between 76% and 81% and the expansion valve had the highest exergy efficiency of 93%.

In the study conducted by Acar et al. [21], it was determined that HPD systems could operate in harmony with renewable energy sources. Considering this information, Sevik [22], who met the electrical needs of an HPD system with a photovoltaic (PV) system, provided the heat energy needs of the system with a double-pass air-solar collector. The COP values of the entire system for tomato, parsley, strawberry and mint products were determined to be 1.96, 2.17, 2.27 and 2.28, respectively. Candan et al. [23], who conducted studies on sustainable agricultural practices, examined the instantaneous energy performance in a PV-supported HPD system. The energy efficiency of the PV-assisted HPD system during drying of banana chips was determined to be 48% on average. Yao et al. [24] conducted tests on the drying kinetics of grapes in a solar collector-integrated HPD system. The authors expressed that the average COP value of the HPD system with solar collector support reached 3.26 from 2.26. Atalay et al. [25] established the total exergy destruction of the drying cabinet and compressor during the drying process in a PV-supported HPD system as approximately 75%.

One of the latest technologies in food drying applications is infrared (IR) dryers. IR dryers are generally used by placing them inside the drying cabinet or on conveyors [26–28]. Aktas et al. [29] goaled to identify the effectiveness of both systems on drying kinetics by drying 15 mm thick stale bread slices in IR dryer and HPD experimental systems. The drying efficiencies of HPD and IR dryer systems were calculated as 25% and 39%, respectively. The authors emphasized that both drying systems have a significant effect on moisture removal processes. Wang et al. [28] developed a temperature-controlled IR-assisted forced convective dryer and compared the results with conventional hot air drying and advanced microwave vacuum drying. The authors defined that IR drying at 2.5-3.0 μm wavelength was more effective than 5.0-6.0 μm wavelength. Furthermore, it was found that IR dried products had less shrinkage, brighter color and better re-moisturizing capacity than traditional hot air dried products. The best drying condition for squid was determined to be 0.5 m/s air speed and 2.5–3.0 μm wavelength. Singh et al. [30] investigated the drying of banana chips dried at 0.8 m/s air speed in HPD, IR-assisted HPD, solar-assisted HPD and solar-IR-assisted HPD systems and evaluated the performances of the systems. It was appointed that the solar-assisted HPD system had the highest energy and exergy efficiencies (59% and 24%, respectively). On the other hand, the highest average SMER value was specified as 1.1618 kg/h in solar-IR assisted HPD systems. The results of the study showed that hybrid systems consisting of different drying systems such as heat pump, solar and IR gave more successful results for faster food drying.

Film heaters made of carbon fiber material can provide an easy and effective solution to meet the production quality and energy efficiency requirements of modern industry. Carbon fiber film heaters (CFH), which have a wide range of use in various industrial areas, are preferred in the heating sector thanks to their advantages such as fast heat dissipation and wide temperature tolerances. On the other hand, the homogeneous temperature distribution of carbon heaters thanks to the film structure plays a key role in providing good quality dried products.

Cokgezme et al. [31] dried strawberry slices at 55, 60 and 65°C in the CFH drying system and determined the drying times as 318, 258 and 251 minutes, respectively. On the other hand, the energy efficiency of the system at 55 and 65°C drying temperatures was calculated as approximately 27% and 32%. Icier et al. [32] thawed frozen potato cubes with microwave, conventional, ohmic and carbon fiber plate supported cabinet heater techniques. The longest thawing time (5360 s) in the study occurred in the carbon fiber plate supported cabinet heater due to its low temperature. In another study by the authors [33], the quality of the products and energy-exergy efficiencies were investigated using IR and CFH drying methods. More color change occurred in the products dried with the IR drying method compared to the CFH drying method. In addition, the total phenolic content of the products was better preserved in IR drying. The exergy efficiencies of the IR and CFH drying systems were determined to be approximately 10 and 32%, respectively.

In the light of literature research, studies are encountered in which products are dried with the help of infrared-supported heat pump drying systems or carbon fiber film heaters [34]. However, it has been identified that drying studies conducted with carbon fiber film heaters are limited to a few studies. In addition, the authors have not encountered a study in which the performance analysis of a heat pump drying system supported by both infrared and carbon fiber film heaters was conducted. To fill this research gap in the literature, a new HPD system supported by both IR and CFH was formed in this study and the performance analyzes of the system in the drying process of apple slices were experimentally explored. The integration of an infrared lamp and a carbon fiber film heater with an average power of 50 and 75W, respectively, into the HPD system highlights the novelty of this study. Finally, this study aimed to determine the effects of infrared and carbon fiber film heaters on drying time and energy consumption.

2. MATERIAL AND METHODS

Turkey, along with China and the USA, is among the top three leading producers of annual apple production. According to the Turkish Statistical Institute (TUIK) data, the total amount of apples harvested in Turkey was 4,602,517 tons in 2023 [35]. The "starking delicious" variety of apple is preferred as the product in this study since the apple is consumed a lot by the society. Besides, thanks to the existence of numerous scientific studies on drying apple slices using different methods in the literature, it is anticipated that the study findings will have an effective widespread impact [36]. For each experiment, 600g of apples obtained from a commercial enterprise were sliced evenly at 3 mm thickness with the help of a slicer.

2.1. Measuring Equipment and Experimental Method

In the experiments carried out in an HPD test system, there was no air inlet or outlet to the system, and the system was used in accordance with the closed loop principle. The basic elements of the system are the compressor, condenser, evaporator and expansion valve (capillary tube), while an external evaporator and condenser were placed on the loop line to improve the system performance. In addition, the solenoid valves in the system are opened and closed with the help of a digital thermostat, allowing the external evaporator and condenser to be automatically activate or deactivate. The condensed water in the evaporator is transferred to the outside of the system with the help of a flexible hose and concave condensation tank.

The appearance of the IR and CFH supported HPD experimental system was given in Figure 1, and the technical specifications of the equipment used in the system were given in Table 1 [20].

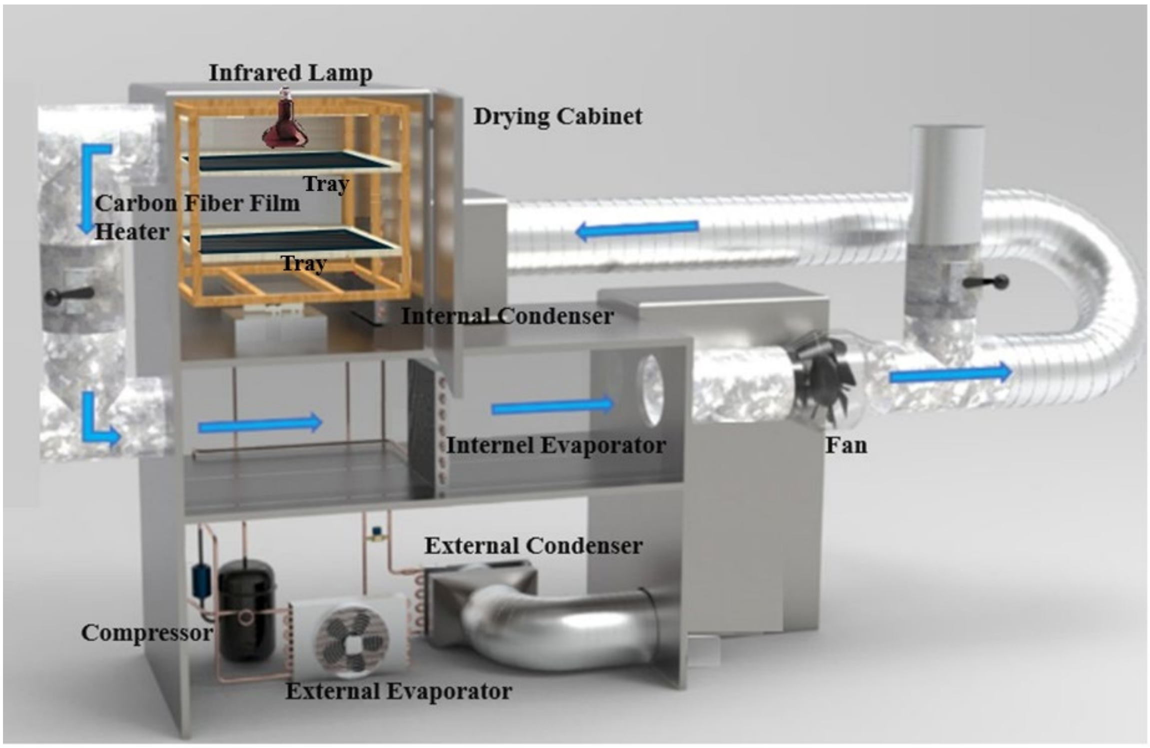

Figure 1. HPD experimental system supported by infrared and carbon fiber film heater

Table 1. Technical specifications of the equipment used in the experimental system

System Elements	Type	Heat Transfer Surface (m^2)	Rated Power (W)
Compressor	Rotary	N/A	750
External Evporator	Aluminum Lamella	2.78	N/A
External Condenser	Aluminum Lamella	1.56	N/A
Internal Evaporator	Aluminum Lamella	2.78	N/A
Internal Condenser	Aluminum Lamella	3.60	N/A
Expansion Valve	Capillary tube Lenght: 1m	N/A	N/A
Fan of Drying Cabinet	Axial	N/A	50
Fan of External Condenser	Axial	N/A	33
Fam of External Evaporator	Axial	N/A	33
Refrigerant	R410A	N/A	N/A
Infrared Lamp	620-750 nm wavelength range	N/A	50
Carbon Fiber Film Heater	N/A	0.19	55

A 50W IR lamp was placed on the top of the drying cabinet in the HPD experimental set given in Figure 1, 15 cm above the products, while a CFH was cut to cover the bottom surface of two trays, each 0.46m × 0.42m in size, where the products were located (Figure 2). The wax paper was used to prevent the apple slices from directly contacting the CFH and the tray surface. Therefore, the tray arrangement was formed from top to bottom in the form of apple slices, wax paper, CFH and a tray with a perforated surface made of stainless steel. There was no space left between the tray arrangement.

In all experiments conducted under laboratory conditions, the ambient temperature was set to 22°C and the relative humidity to 45%. In the first stage of the study, only the HPD system was used (Scenario-I), while in the second stage, the IR and CFH operated continuously with the HPD system (Scenario-II). For both scenarios, the speed of circulation air of the HPD system was determined as 1 m/s. Furthermore, studies in the literature [37] emphasize that apple slices dried at mild temperature (40ºC) are approximately 50% richer in polyphenols than slices dried at high temperature (65ºC). Therefore, in this study, the cabinet temperature was kept constant at 40±1°C. The system was operated before the products were placed in the drying cabinet, and the trays with sliced apples were placed in the cabinet when the continuous conditions were provided.

(a) (b)

Figure 2. (a) Carbon fiber film heater (CFH), (b) infrared (IR) lamp

For both scenarios, the experiments started with the placement of the trays in the drying cabinet and the system performance was monitored throughout the 6-hours experiment period. Product weight and temperature data were recorded at 5 minutes intervals, and system pressure and power consumption values were recorded every 60 minutes. The number and technical specifications of the data recording and measuring devices used in the experiments are given in Table 2.

2.2. Mathematical Method

In this study, the weight loss in the products and the energy consumption of the system for the Scenarios-I and II specified in the previous section were obtained experimentally. However, mathematical solutions were needed to evaluate the system performance.

Thermophysical properties of the loop air used in the experimental system were obtained from thermodynamic tables by taking into account the temperature and pressure conditions. The flow rate of the loop air ($\dot{m}_h$) was calculated with Equation 1 and the heating and cooling capacities in the condenser and evaporator ($\dot{Q}_k$ and $\dot{Q}_e$) were calculated with Equations 2 and 3.

Table 2. Data recording and measuring devices used during the experiment

Measurement	Measuring Device Brand	Measure range / Accuracy
Product Weight	ESIT SSP-40 Load cell	0–40 kg / ±0,04 g
Air speed	TESTO 405	0,1–10 m/s / ±0,1 m/s
Pressure	TESTO 570-2 Digital manifold	0–50 bar / ±0,1 bar
Temperature of Drying Cabinet	EVCO evkb21 NTC Digital thermostat	-50 – 130°C / ±0,1°C
Temperature and Humidty	Elitech GSP-6	-40–85°C / ±0,5°C %10–99 / ±%3
Power of system and compressor	Koodmax	200–276 VAC / ±%1,5 VAC 0,005–16 A / ±%2 A

$$\dot{m}_h = A.\rho.\vartheta \tag{1}$$

$$\dot{Q}_c = \dot{m}_h.C_p.(T_{c,o} - T_{c,i}) \tag{2}$$

$$\dot{Q}_e = \dot{m}_h.C_p.(T_{e,i} - T_{e,o}) \tag{3}$$

Here; A: surface area (m^2), ρ: air density (kg/m^3), ϑ: air speed (m/s), C_p: specific heat (kJ/kg K) are defined. In addition, T_i and T_o represent the inlet and outlet temperatures (K), and the subscripts c and e represent the condenser and evaporator.

The COP value for the heat pump was calculated with Equation 4 to compare the system performance. The power values consumed by the compressor ($\dot{W}_{cp}$) were determined experimentally.

$$COP_{HP} = \frac{\dot{Q}_c}{\dot{W}_{cp}} \tag{4}$$

The arithmetic means of the COP_{HP} values obtained throughout the experiments were obtained as in Equation 5.

$$Mean\ Value = \frac{1}{n}\sum_{k=1}^{n} x_k \tag{5}$$

The amount of energy consumed in return for the moisture extracted from the product is defined as the specific moisture extraction rate (SMER) while the SMER values for both scenarios considered in the study were calculated with the help of the equation given in Equation 6 [38].

$$SMER = \frac{m_i - m_s}{\dot{W}_{cp} + \dot{W}_{fan,i} + \dot{W}_{fan,o} + \dot{W}_{IR} + \dot{W}_{CH}} \tag{6}$$

3. RESULTS AND DISCUSSION

In this study, the effects of IR and CFH systems on drying, energy consumption and system performance were investigated by considering two scenarios which only the HPD system, and the IR and CFH supported HPD system were used. In both scenarios, the systems were expected to reach steady conditions (40°C) before the products were placed in the drying cabinet. The time for the system to reach steady conditions was 22 minutes in Scenario-I while this time was measured as 11 minutes in Scenario-II. This result demonstrated that IR and CFH accelerated the system to reach steady conditions in Scenario-II.

The weight losses in the products during the experiments for Scenario-I and II were given in Figure 3. The products, which initially weighed 600 g, decreased to 159 and 118 g in Scenario-I and II, respectively, at the end of the experiments. Therefore, at the end of the experiments, the weight difference in both scenarios was determined to be approximately 35%. The main reason for this difference was the support of IR and CFH used in Scenario-II to the heating load. On the other hand, the system reaching the drying temperature quickly in Scenario-II provided a fast dehumidification process. In Scenario-I, the products reached 200 g in approximately 310 minutes while this period was determined as approximately 250 minutes in Scenario-II.

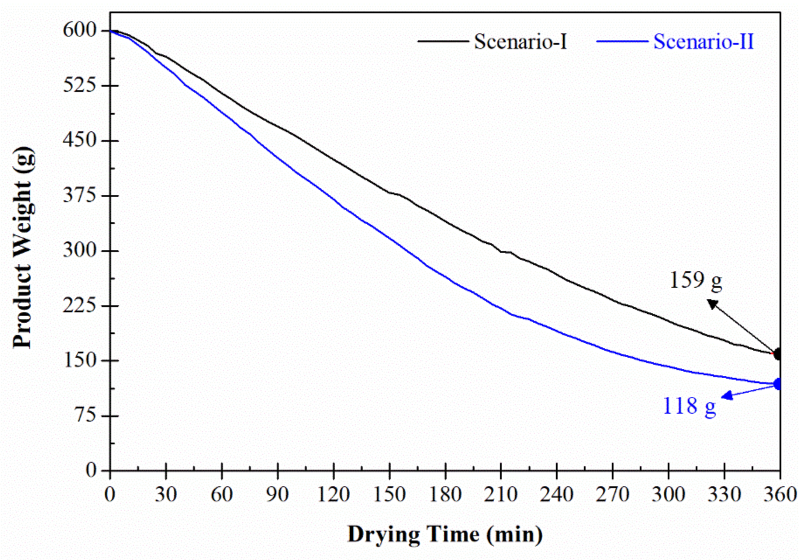

Figure 3. Weight loss of products for Scenario-I and II

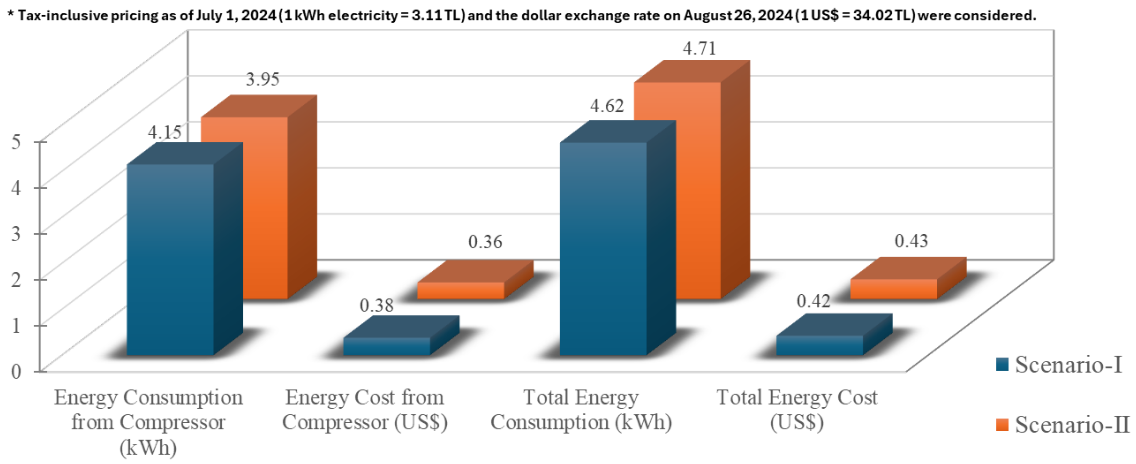

Figure 4. Energy consumption and cost of the system and compressor for Scenario-I and II

The energy consumption and cost originating from the system and compressor for Scenario-I and II were given in Figure 4. The energy consumption and cost originating from the compressor were decreased by approximately 5% thanks to the integration of IR and CFH into the HPD system. In Scenario-II, the cabinet temperature reached the drying temperature more frequently compared to Scenario-I, and it resulted in the external condenser being activated more often. Therefore, the condensing pressure and compressor load decreased. However, for the six-hours experiments, the use of IR and CFH in Scenario-II increased the total energy consumption and cost of the system by approximately 2%. However, since it took 290 and 225 minutes for the products to drop to 200g in Scenario-I and II, respectively, the total energy consumption of the system during this period was determined as 3.7 and 2.9 kWh. As a result, the use of Scenario-II for 400 g moisture extraction reduced the drying time by 28% compared to Scenario-I and provided about 25% energy savings.

The SMER data calculated by considering the energy consumption data of the system and the product weights recorded every hour during the experiments were presented in Figure 5. The SMER value, which was approximately 0.12 kg/kWh at the beginning of the experiment in Scenario-I, was specified as approximately 0.15 kg/kWh in Scenario-II. In both scenarios, a rapid decrease in SMER values was observed after the third hour of the experiments. The SMER values for Scenarios-I and II were recorded as approximately 0.06 and 0.03 kg/kWh, respectively, at the end of the experiments. The average SMER values for both scenarios were approximately 0.1 kg/kWh. These values were approximately 0.7 and 0.8 kg/kWh lower compared to the results of Refs. [4] and [18], respectively. Utilizing a lower amount of product (600g) than the system capacity in the experiments resulted in lower SMER values obtained in this study.

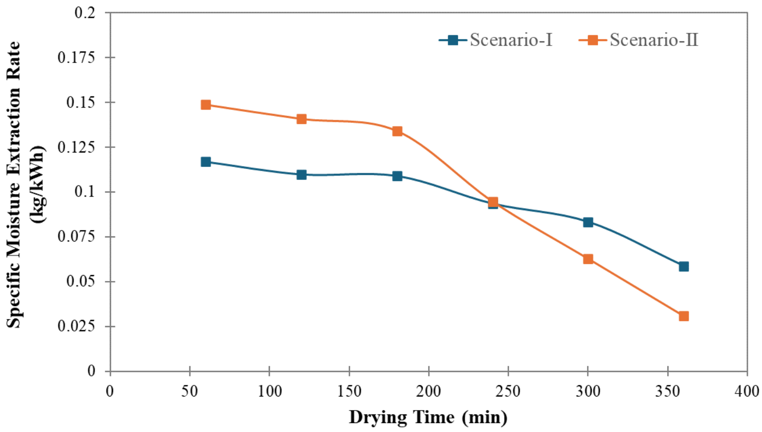

Figure 5. SMER values for Scenario-I and II

The thermal images of the products taken from the cabinet with the help of a Fluke-Ti9 brand thermal camera were given in Figure 6 at the end of the experiments. In Scenario-II, the continuous operation of the CFH provided more homogeneous heating and drying of the apple slices placed on the tray surface. For both scenarios, the maximum surface temperatures of the products were approximately 44°C, while the minimum were 35°C. On the other hand, the average surface temperatures of the products were about 36°C in Scenario-I and 39°C in Scenario-II. In Scenario-II, the IR lamp located on the upper wall of the drying cabinet and the CFH placed under the trays supported the product temperatures to be higher than in Scenario-I.

To determine the differences in the loads of the system components for Scenario-I and II, the capacities of the internal condenser and evaporator were calculated using Equations 2 and 3. In Scenario-I, the condenser and evaporator capacities were established as 2.89 and 2.22 kW, respectively, while in Scenario-II these values were determined as 2.69 and 2.35 kW, respectively. The lower condenser capacity in Scenario-II compared to Scenario-I was due to the condenser load reduction of the IR and CFH equipment. As a result of this, as previously mentioned, the amount of energy consumed by the compressor decreased proportionally. In addition, COP values were evaluated according to the heat pump since the system was used in heating mode in both scenarios. The COP_{HP} value, which was 4.09 in Scenario-I, increased by 0.09 in Scenario-II and was determined as 4.18. Therefore, the use of IR and CFH supported HPD system resulted in a 2% increase in COP_{HP} value compared to an ordinary HPD system. Instantaneous measurement and evaluation of heating capacity and compressor work consumption caused the increase amount determined for COP_{HP} to be low.

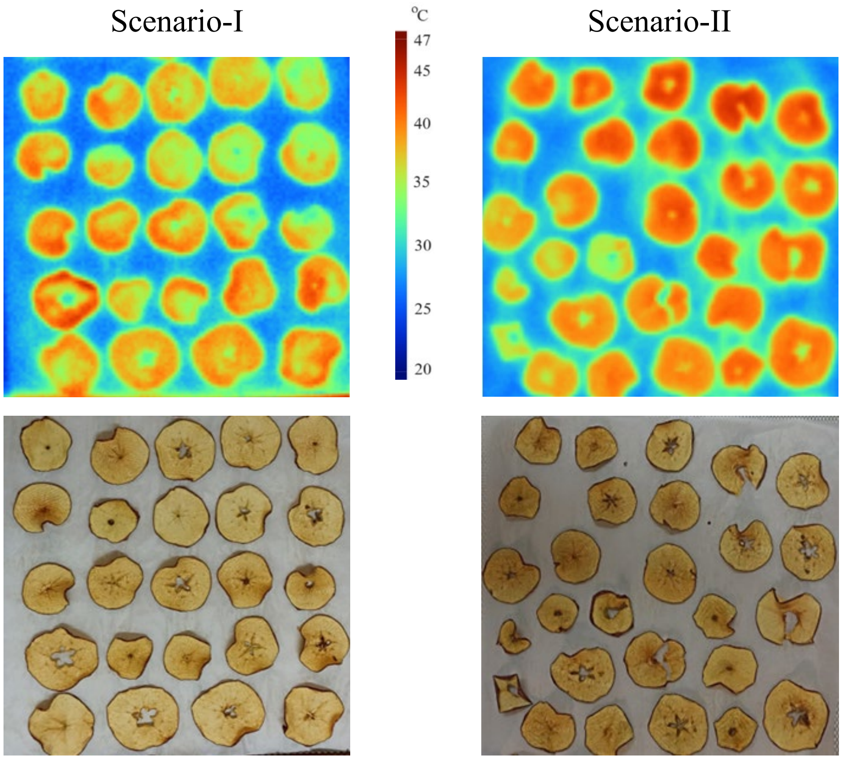

Figure 6. Thermal images of products after drying for Scenario-I and II

4. CONCLUSIONS

In this study, an infrared lamp and a carbon fiber film heater were integrated into a typical air-source closed-loop heat pump drying system and their effects on the moisture absorption performance, energy consumption, and COP values were investigated. A typical heat pump drying system was called Scenario-I, while Scenario-II represented the IR and CFH supported heat pump drying system.

The results obtained during the drying process of apple slices under experimental conditions showed that Scenario-II improved the drying time. In the study, with IR and CFH support, a 50% decrease was achieved in the time for the system to reach continuous conditions, while a 2% decrease was observed in the energy consumption and cost originating from the compressor. On the other hand, in the six-hours experiments, although there was a 0.09 kWh increase in the total energy consumption of the system in Scenario-II compared to Scenario-I, the 28% shortening of the time until the product weight decreased to 200 g provided approximately 25% energy saving. Furthermore, the approximately 2% increase in the COP_{HP} value in Scenario-II showed that the use of IR and CFH together with the HPD system was appropriate. Therefore, IR and CFH supported HPD systems can be preferred for fast drying processes that require low compressor load.

In future studies, intermittent use and duration of carbon fiber film heaters can be investigated depending on the type of product and the amount of moisture it contains. To comprehensively examine the effects of IR on drying performance, it is recommended that studies addressing the number, power and location of IR be conducted. In addition, the effect of heaters placed in the drying cabinet on air flow should be examined and the contributions of positioning in different areas such as the system channel to drying performance should be evaluated.

NOMENCLATURE

c	Condenser	HPD	Heat pump drying
CFH	Carbon fiber film heaters	IR	Infrared
COP	Coefficients of performance	PV	Photovoltaic
cp	Compressor	SMER	Specific moisture extraction rate
e	Evaporator	TUIK	Turkish Statistical Institute
HP	Heat pump		

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Ümit İşkan: Conducted the experiments, analyzed the results, and wrote the manuscript.
Ahmet Yüksel: Performed the experiments, wrote, and revised the manuscript.
Cüneyt Tunçkal: Conducted the literature research and performed the experiments.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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