HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

Performance evaluation of solar chimney applied for drying processes

DOI: 10.54598/003170

PhD Thesis

by

Gebremicheal Gedion Habtay

Gödöllő
2022

Doctoral school

Denomination: Doctoral School of Mechanical Engineering

Science: Mechanical Engineering

Leader: Prof. Dr. Gábor Kalácska, DSc
Institute of Technology
Hungarian University of Agriculture and Life Sciences,
Gödöllő, Hungary

Supervisor: Prof. Dr. István Farkas, DSc
Institute of Technology
Hungarian University of Agriculture and Life Sciences,
Gödöllő, Hungary

Co-Supervisor: Dr. János Buzás, PhD
Institute of Technology
Hungarian University of Agriculture and Life Sciences,
Gödöllő, Hungary

....	....
Affirmation of supervisor	Affirmation of head of school

CONTENTS

1. INTRODUCTION, OBJECTIVES

The majority of energy is produced from non-renewable sources are fossil fuels, which supply about 80% of the world’s energy. Solar energy is a limitless resource with the potential to meet a significant portion of the world’s future energy demands. Low-temperature solar dryers are cost-effective ways to guarantee food security and are suited for farmers in both developing and developed countries. The solar dryer’s drying process entails brining the moisture content to an acceptable level, which is usually between 10–20%. Harnessing solar energy is a viable strategy to meet the demands posed by the drying process.

Natural type solar dryers are regarded as having lower performance and being cheaper than forced type dryers due to the absence of external driving devices. Their ineffective performance is caused by a low air flow rate. With the use of solar chimney, the air flow rate can be enhanced. However, the lack of reliable experimental investigations on solar chimneys, particularly those employed in natural type indirect solar dryer (ISD). Therefore, the main aim of the current research is to experimentally examine parametric evaluation of various solar chimney designs. The detailed research objectives are as follows:

- To study the effect of solar radiation and ambient temperature on the performance of ISD.
- To examine the effect of the type of solar chimney (SC) height and air gap thickness on temperature rise and air flow rate of the dryer under both no-load and load conditions.
- To change the SC’s stack height and air gap thickness, then evaluate how these changes affect the dryer unit’s energy efficiency (energy and exergy analysis).
- To estimate moisture loss of dried product (apple slices) using proposed SC designs and compare them with the conventional dryer and open sun drying (OSD).
- To investigate and compare the effect of types of SC on energy consumption and drying efficiency.
- To perform experiments in order to compare the collected data and recommend the optimum arrangement for achieving the highest level of performance.

2. MATERIALS AND METHODS

This chapter covers the description of the materials, techniques, and equipment used, as well as the scientific methodologies employed in the experimental measurements to accomplish the research goals.

2.1. Description and experimental set up

The novel indirect solar dryer (ISD) was constructed and tested using various solar chimney designs at the Solar energy laboratory of the Hungarian University of Agriculture and Life Sciences (MATE), Gödöllő, Hungary, between June–August 2020, 2021, and July 2022. A single-pass solar air collector (SAC), drying chamber, and solar chimney (SC) are all part of the solar-based drying system (ISD) as shown in Fig. 1.

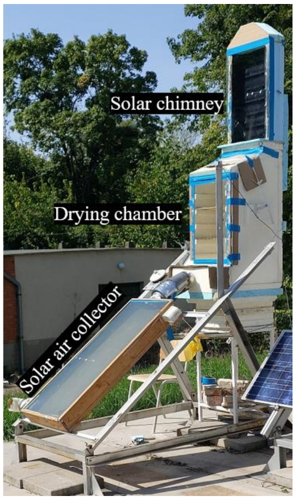


Fig. 1. Complete view of a novel indirect solar dryer

A single-pass solar air collector (SAC) was made with a 4 mm thick plexiglass material to transmit the incoming shortwave solar radiation to the plate. A 1.2 mm thick copper plate selectively painted with enamel paint. The width and length of the absorber surface were 0.460 and 1.226 m, respectively. The channel gap between the absorber plate and the glazing cover was 10.8 mm. The SAC is oriented facing south and tilted at 45° to the horizontal. Its outlet was connected to the drying chamber through a PVC duct. The rectangular drying chamber, which contains the food to be dried, was built from 0.5 m thick expanded polystyrene (EPS). The external dimension of the drying chamber is 0.5 m length, 0.5 m width, and 1.0 m height equipped with two drying trays of size 0.38 m by 0.40 m made from the plastic net. The top aperture of the drying chamber has solar chimney attached to it. The rectangular-shaped SC consists of an absorber plate made up of 5 mm thick double-face corrugated cardboard, a 4 mm thick Plexiglas, and a 50 mm thick expanded polystyrene (EPS) box. The absorber plate was painted black, and an aluminium fin attached to it. The air flow gap is formed by the glass cover and absorber plate. Fig. 2 shows the construction details of a proposed solar chimney.

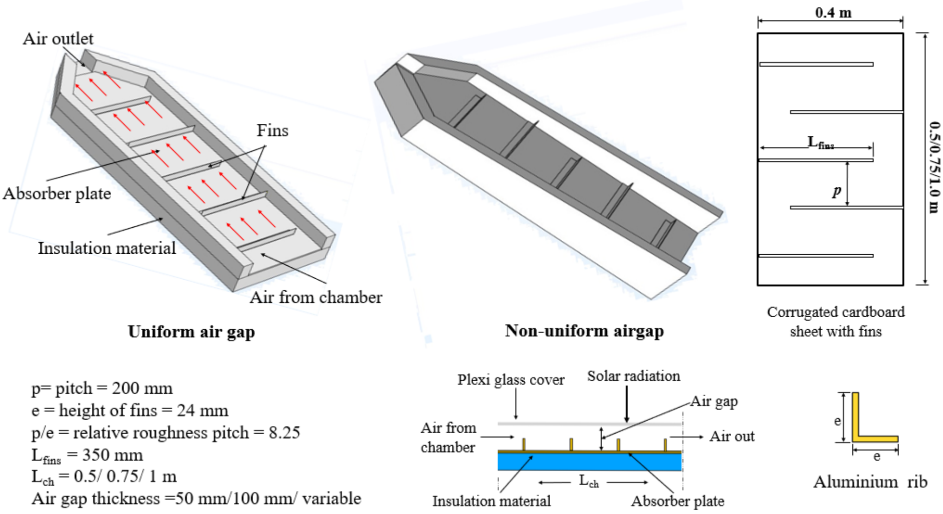


Fig. 2. Proposed solar chimney design

2.2. Instrumentation and experimental procedure

In this research work, seven detachable solar chimney designs have been proposed as shown in Table 1.

Table 1. Proposed solar chimney design

Chimney configuration	**Chimney width (m)**	**Chimney stack height (m)**	**Chimney air gap (mm)**
Case_1	0.5	1	50
Case_2	0.5	0.75	50
Case_3	0.5	0.5	50
Case_4	0.5	1	100
Case_5	0.5	0.75	100
Case_6	0.5	0.5	100
Case_7	0.5	1	*Non-uniform
Case_8	Convectional ISD		
OSD			

Note: *non-uniform: cross-sectional area changes with SC height (decreases towards the SC outlet) and glass cover tilted 86° from vertical.

Throughout the trials, various operating parameters were measured using different measuring devices (Fig. 3). Pyranometer (model: Kipp and Zonen MM11, Delft, the Netherlands; accuracy: ±0.1 $W.m^{-2}$; range: 1– 4000 $W.m^{-2}$) and solarimeter (model: KIMO SL200, France; accuracy: ±1 $W.m^{-2}$; range: 1–1300 $W.m^{-2}$) were used to measure solar irradiance on collector and chimney surfaces. Temperatures at different location of the dryer were measured with 10 calibrated thermocouples (type: T-type, TT-T22S, UK; accuracy: ±1 °C; range: -270–370 °C). The temperatures (T-type) and solar radiation (Pyranometer) were recorded every 1 min intervals and connected to the computer using ADAM data Acquisition (model: ADAM 4018 Advantech, Taipei, Taiwan; accuracy: ±0.1%). The air mass flow rate in the ISD is measured with Testo anemometer was placed in the SAC inlet port (model: Testo 405i, Germany; accuracy: ±0.1 m s^{-1}, range: 0–30 m s^{-1}). Thermo-hygrometer (model: Gove H5075, Shenzhen, China; temperature accuracy: ±0.32 °C; RH range: 0–99% with accuracy of ±3%) was used to measure the relative humidity inside the drying chamber. An electronic moisture analyser (model: Sartorius MA 30, accuracy: ±0.05% MC, range: 0–100%MC) was used to estimate the initial moisture content of the apple slices and a digital balance (model: APTP457, CGOLDENWALL, accuracy: ±0.1 g; range: 0–5 kg) was used to record the moisture loss of the sample. The measurements were taken for eight hours starting from 09:00 until 17:00. During under-load conditions tests, the product's moisture loss was measured every 2 hours.

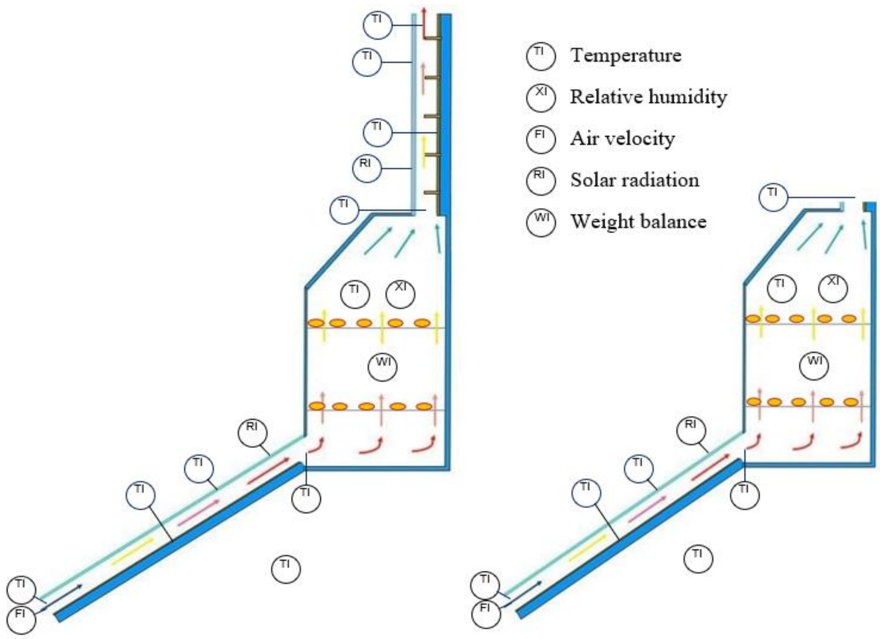


Fig. 3. Schematic diagram of measuring instrument location

2.3. Equations used to evaluate the proposed dryer

In this section, the parameters used to evaluate the ISD's performance are presented.

2.3.1. Energetic analysis

Based on the first law of thermodynamics, the useful heat gain, Q_u, under steady-state conditions expressed as:

$$Q_u = \dot{m}_a\, C_p(T_o - T_i) = A_c\, F_R\, [I_T(\tau\alpha) - U_o(T_i - T_a)]. \quad (1)$$

Then the energy efficiency of the SAC according to ASHRAE is:

$$\eta_I = F_R(\overline{\tau\alpha}) - F_R U_o \left(\frac{T_i - T_a}{I_T}\right). \quad (2)$$

2.3.2. Exergetic analysis

The exergy of the SAC determined by the flowing air is exhibited as:

$$Ex_u = \dot{m}_a C_p \left[(T_o - T_i) - T_a \left(\ln\left(\frac{T_o}{T_i}\right)\right)\right]. \quad (3)$$

The input exergy of the solar radiation is expressed as:

$$Ex_i = I_T A_c \left[1 - \frac{T_a}{T_s}\right]. \quad (4)$$

The exergy efficiency of the SAC is articulated as:

$$\eta_{II} = Ex_u / Ex_i. \quad (5)$$

2.3.3. Performance of drying apple fruits

The instantaneous moisture content of the samples during the drying time can be estimated as:

$$MC(t) = \left(m(t) - m_{dry}\right)/m_{dry}. \quad (6)$$

The specific energy consumption (SEC) was calculated as:

$$SEC = {}^{Q_u}\!/_{m_w}. \quad (7)$$

The drying efficiency (η_d) is determined as:

$$\eta_d = \frac{m_w\, h_{fg}}{Q_u}. \quad (8)$$

The amount of water (m_w) removed from the dried product is calculated as:

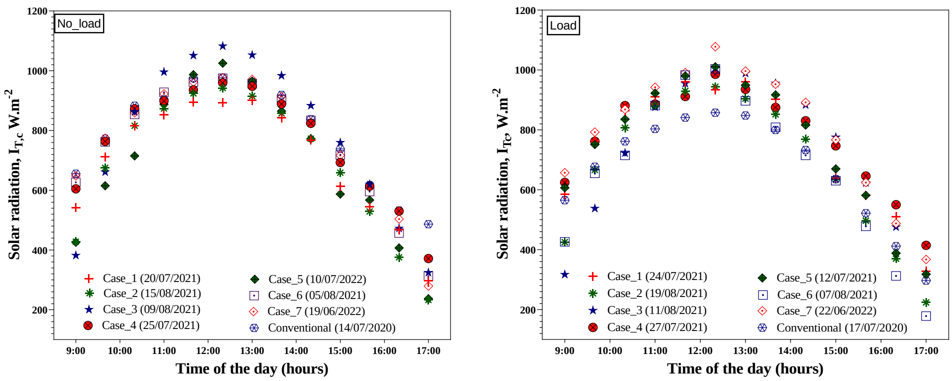
$$m_w = m_p \frac{\left(MC_i - MC_f\right)}{100 - MC_f}. \quad (9)$$

3. RESULTS

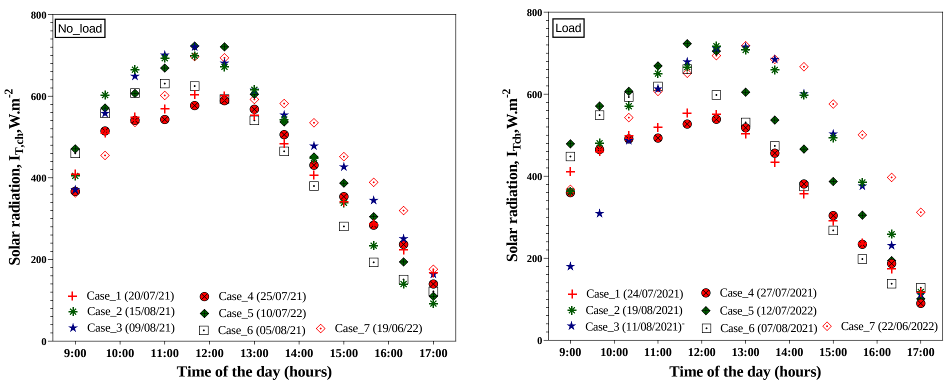
This chapter presents the most important results obtained from the experimentation and their discussions.

3.1. Effect of solar radiation and ambient temperature

Fig. 4 and Fig. 5 depicts the variation in solar radiation on collector and chimney surfaces and ambient temperature over the course of the experimentation days under no load and load conditions. The figures depict the fluctuation of solar radiation at collector and chimney surfaces as a function of the time of day. Both gradually increased in morning, reached a high at noon, and then started to decrease in the afternoon.



a)



b)

Fig. 4. Variation of solar radiation at: a) collector; b) chimney surfaces

The trend and magnitude of the instantaneous solar radiation is the key input parameter to determine the performance of the solar dryer. The maximum solar intensity was observed between 11:50 and 12:30 h and was in the range of 920–1083 W.m^{-2} for solar radiation on collector surface. The maximum solar radiation intensity of 1083 W.m^{-2} was reported for Case_3, while Case_1 had the lowest (920 W.m^{-2}) in this time ranges. The solar intensity is much lower on the chimney surface than on the collector surface, which has an average solar intensity of about 37%, because of the surface orientation. Cloud cover and wind speed during various experiment days were the main contributors to variations in solar radiation and ambient temperatures. The daily solar radiation recorded varied from 213 to 1083 W m^{-2} and 90 to 740 W m^{-2} at collector and chimney surfaces. The maximum ambient temperature was measured 2–3 h after the peak sunshine hours. The ambient temperatures ranged from 18–37 °C. The average ambient temperature for July was found to be 1.1 and 2.8 °C higher than for June and August, respectively.

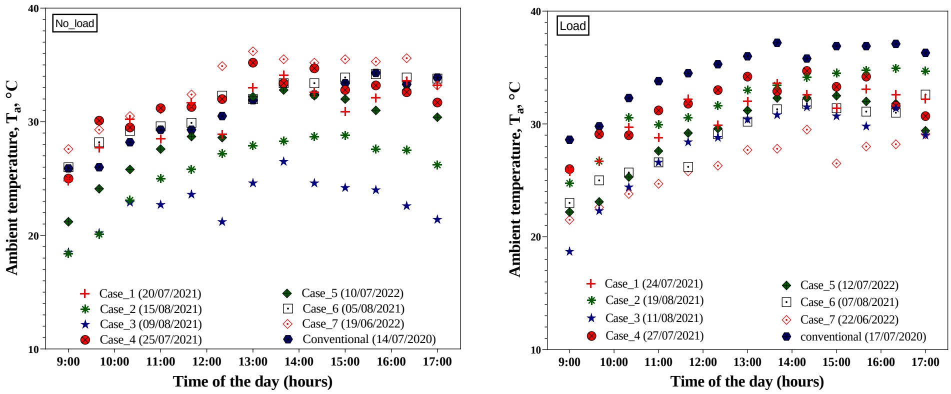


Fig. 5. Variation of ambient temperature

3.2. Effect of type of solar chimney under no-load conditions

3.2.1. Effect of type solar chimney on temperature rise

The impact of stack height on temperature rise in the SAC is also depicted in Fig. 6. According to the figure, the maximum and average air temperature rises were 26 and 18 °C, 27 and 21 °C, 32 and 25 °C, 25 and 16 °C, 24 and 18 °C, 25.7 and 19 °C, 27 and 18 °C, for Case_1 through 7, respectively. As seen from the figure, the temperature rises in the SAC rose by about 7.5 °C as the air gap thickness reduced from 100 to 50 mm. Moreover, as the stack height increases from the 0.5 m to 1 m the effect of air gap thickness becomes negligible.

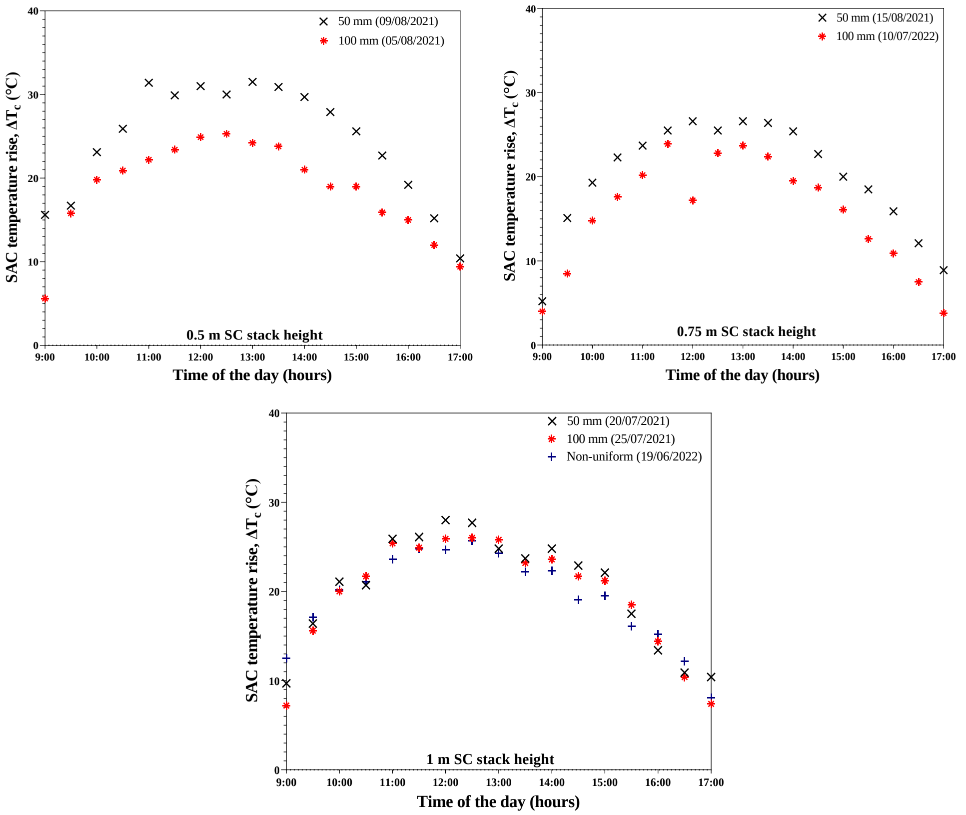


Fig. 6. Comparison of the SAC temperature rise based on SC stack height

3.2.2. Temperature variation on drying chamber

The hourly variation of drying air temperature in the drying chamber were to varied from 34 to 63.5 °C, 39 to 68.5 °C, 40 to 70 °C, 40 to 59 °C, 42 to 66 °C, 44 to 67 °C, 33 to 58 °C, and 43.5 to 61 °C, respectively, for novel dryers (Case_1 to Case_7) and conventional dryer with their corresponding relative standard deviations of 17.6, 18.2, 12.6, 17.4, 17.1, 12.1, 10.0, and 14.3%. These variations on air temperature can be explained due to the variation of solar insolation in each trial as well as the outlet temperature of the SACs. The drying air temperature above 45 °C was achieved in each configuration between 10:00 and 16:00, with the exception in some configurations due to cloudiness.

3.3. Effect of type of solar chimney under full load conditions

This section presents the results and analyses of the effect of different solar chimney configuration on performance of the dryer under load conditions. During the experimentation days, the ambient temperature, solar radiation at

SAC and SC were in the range of 19–37 °C, 224–1078 Wm^{-2} and 90–740 Wm^{-2}, respectively.

3.3.1. Type of solar chimney on temperature rise and mass flow rate

According to the SAC temperature measurement, the average values of the collector's inlet, outlet and absorber temperatures were 32, 52, and 74 °C for Case_1, 33, 54.5, and 78 °C for Case_2, 29, 51 and 68 °C for Case_3, 33, 51.5 and 72 °C for Case_4, 28, 46.5, and 63 °C for Case_5, 31, 57, and 72 °C for Case_6, 28, 49, and 68 °C for Case_7 and it was 36, 56.5, and 75.5 °C for conventional dryer, respectively. It was found that an average air temperature difference of 17.5 and 28 °C between the collector's outlet and inlet (ΔT_c) as shown in Fig. 7. The heat losses of the solar collector or solar chimney are significantly influenced by natural convection in the air space between the absorber and the glass cover.

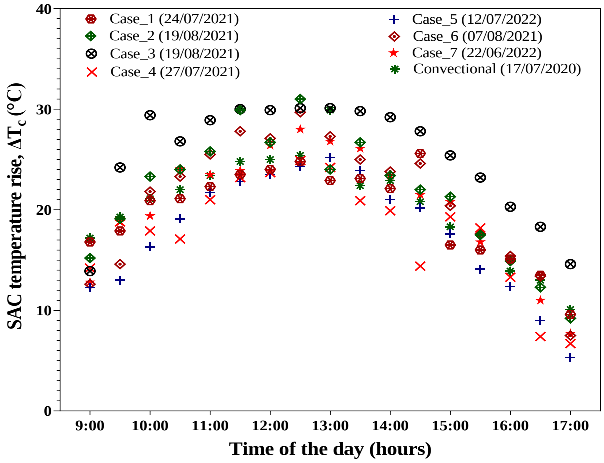


Fig. 7. Temperature rises versus time of the day for SAC for all experimental setups

The ΔT_c was greater for 0.5 m stack height and 50 mm SC air gap followed by Case_2, which was 35 and 31 °C respectively whereas a 1 m stack height and 50 mm air gap found the lowest record. This is due to the high SC height and large air gap, which causes an increase in airflow rate and a drop in ΔT_c. For the same 50 mm air gap, it was found that Case_3 had a ΔT_c of 5.5 °C and 7 °C higher than Case_1 and Case_2 respectively. A 50 mm air gap indicates a temperature rise of between 1 and 4 °C greater when compared to the temperature rise of a 100 mm air gap thickness.

Table 2 shows the effect of types of SC configurations on temperature rise and mass flow rate. It is reasonable to expect that a higher SAC temperature rise will result in a lower air mass flow rate. According to the Table, a non-uniform

SC configuration was found to produce the maximum air flow rate compared to the other settings. This can be explained by the fact that the front wall (glass) of this configuration was inclined to the horizontal, receiving more solar radiation than the other setups. Moreover, a 50 mm air gap SC configuration was found to have a low air flow rate. The air flow rate increased by 31% as the height of the SC stack raised from 0.5 to 1 m. It has been noted that SC stack height and air gap thickness both have an impact on the air flow rate and temperature rise in the SAC. Moreover, according to the results, there was a positive correlation between variations in solar radiation and both the rise in air temperature and the air mass flow rate.

Table 2. Minimum, maximum, average of temperature rises and mass flow rate for all cases

Setup	ΔT_c (°C)			$\dot{m}_a$ (kg s^{-1})		
	Min	**Max**	**Average**	**Min**	**Max**	**Average**
Case_1	10	30	20	0.0086	0.018	0.014
Case_2	9	31	22	0.0068	0.016	0.013
Case_3	14	35	26	0.0045	0.014	0.011
Case_4	7	26.5	18	0.0088	0.021	0.016
Case_5	5	25	18	0.011	0.018	0.014
Case_6	7.5	30	21.5	0.0034	0.016	0.012
Case_7	8	29	21	0.0098	0.021	0.017
Conventional	10	30	20.5	0.0043	0.008	0.007

3.3.2. Impact of solar chimney type on energy efficiency

An energy analysis of the drying system was done to ascertain the effect of the solar chimney type on the system's performance. The energy efficiency of the SAC (η_I) was computed and the results are plotted in Fig. 8. The average instantaneous energy efficiency was 60.12, 63.53, 59.84, 55.52, 61.96, 50.11, 59.98, and 37.82 for Case_1 to 7 and conventional dryer, respectively. The result showed that the highest efficiency was achieved by Case_2, followed by Case_1 (1 m height and 50 mm air gap) and Case_5 (0.75 m height and 100 mm air gap), while conventional dryer had the lowest efficiency. The SC with a 0.75 m height and 50 mm air gap arrangement is therefore the best configuration. The results revealed that the energy efficiency of the novel dryer was increased by 32.5% to 68% when it was compared with the conventional dryer. Results also indicated that it was advantageous to reduce the air gap and raise the SC height to a specific level. The variation of daily useful heat gain $\dot{Q}_u$ ranged from 129.96 to 408.13 W for Case_1, 131.79 to 479.81 W for Case_2, 57.79 to 449.92 W for Case_3, 130.09 to 370.46 W for

Case_4, 103.26 to 411.05 W for Case_5, 75.03 to 356.19 W for Case_6, 147.64 to 429.15 W for Case_7, and it varied between 60.01 and 228.87 W for conventional dryer, (about 75% of the total useful energy found between 10:00 to 14:00). Additionally, the interval between 10:30 and 15:00 found the highest values of the $\dot{Q}_u$ for the novel ISD. A SC with a 50 mm air gap performed better overall than one with a 100 mm air gap, which represented an improvement of 13% in performance. Using the trapezoidal rules, the daily total useful heat gain was determined to be in the ranged of 1.1 to 2.26 kWh.

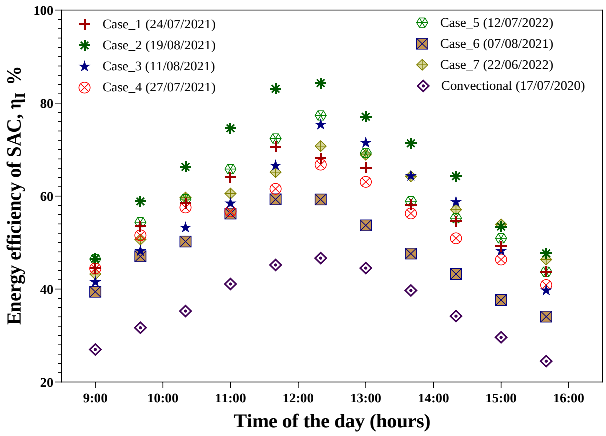


Fig. 8. SAC efficiency comparison for various setups

For same SC height, a 50 mm air gap thickness outperformed one with a 100 mm air gap, while for the same SC air gap thickness, a 0.75 m SC height outperformed than a SC stack height of 1 m and 0.5 m. This is because air flow rate higher for small air gaps. Another finding showed that a SC with non-uniform cross-section setup shows higher value of heat gain than those with constant air gap SC. The figure demonstrates that this is not always the case. It has been found that the SC's stack height and its air gap thickness both have an impact on energy efficiency. Therefore, a mathematical model can be developed in order to show the effect of chimney's height-to-air gap ratio on energy efficiency. It is evidence that while the SAC temperature differential reduces, the mass flow rate increases with the SC height. This demonstrates that optimum mass flow rate and temperature differential for greater efficiency exist at a certain threshold.

Fig. 9 shows empirical relationships between the energy efficiency of the novel and conventional ISD with reduced parameters curve $(T_i - T_a)/I_T$. From the figure, it can be observed that a negative correlation was observed. From this experimental result, the highest effective optical efficiency that can be achieved with SC setup that has an air gap thickness of 100 mm and a stack height of 0.75 m. This is because, when compared to other set ups, this SC setup obtained a better mass flow rate and temperature rise. However, due to the higher temperature rise the heat loss to the ambient is more.

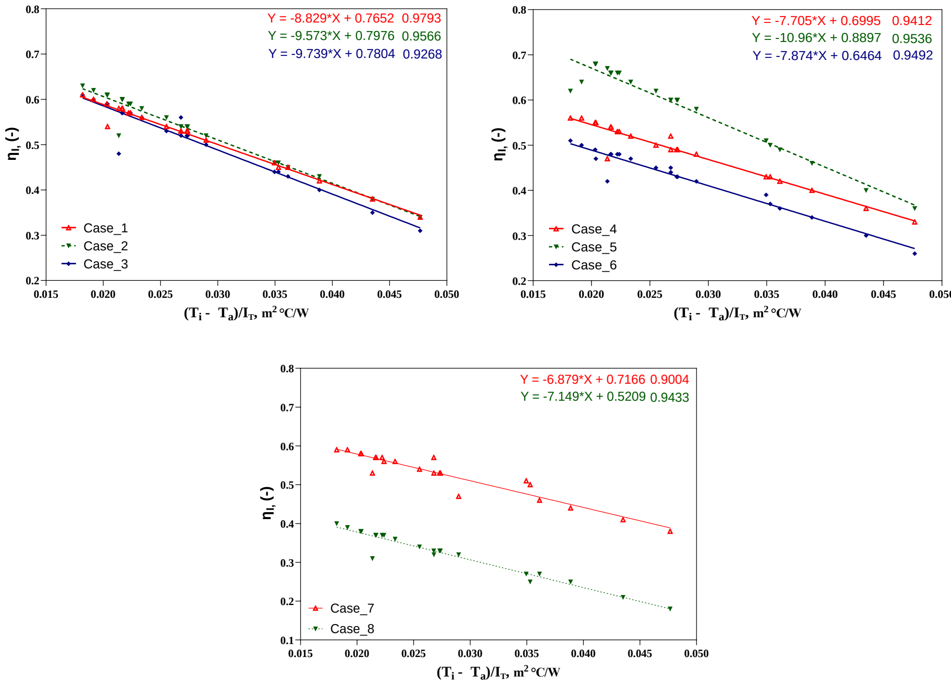


Fig. 9. Correlation between collector efficiency with $(T_i - T_a)/I_T$

Based on experimental results and material properties, the overall heat loss coefficient of SAC was estimated and was found to be 4.03, 3.60, 4.61, 5.33, 4.69, 5.12, 4.50, and 6.35 $Wm^{-2}K^{-1}$ for novel dryers (Case_1 through 7) and conventional dryer, respectively. Higher heat loss occurred on conventional dryer followed by Case_3 and 5. The reason for this can be attributed to the setups' low airflow, which causes the temperature of the absorber plate to rise and increased heat losses to the environment.

Fig. 10 shows the average energy efficiency for a SC for various configurations. As can be seen from the figure, the average efficiencies of the novel ISD (Case_1 through 7) were found to be 12.5, 24.57, 24.81, 10.98, 25.42, 22.61, and 12.64%, respectively and the corresponding overall heat loss coefficients were 6.33, 7.22, 6.38, 6.87, 5.96, 6.55 and 7.41 $Wm^{-2}K^{-1}$, respectively. It has been observed that Case 5 (0.75 m stack height with 100 mm air gap) has a modest advantage over other configurations followed by Case_2 and Case_3 while the lowest energy efficiency was found for SC stack height of 1 m. The figure revealed that while SC stack height had a considerable impact on boosting SC performance, air gap thickness had no discernible effect.

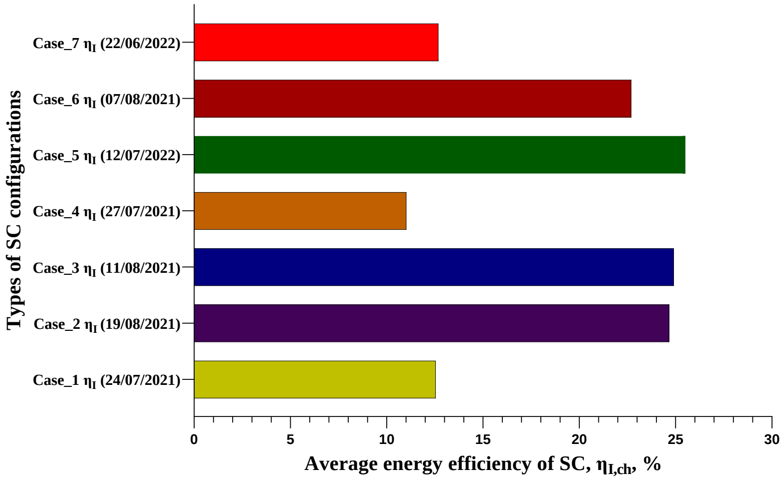


Fig. 10. Average energy efficiency of a solar chimney for all setups

3.3.3. Impact of solar chimney type on exergy efficiency

The exergy destruction, exergy input and instantaneous exergy efficiencies of SAC were computed for various SC arrangements of the novel and conventional dryer. According to the results, the novel dryers' average SAC exergy efficiency for Case_1 through 7 was 27.57%, 31.47%, 27.25%, 25.54%, 28.69%, 22.86%, and 28.02%, respectively, while the conventional dryer achieved its average exergy efficiency of 17.02%. The maximum value was reached with a stack height of 0.75 m and an air gap thickness of 50 mm in a SC arrangement. The novel dryer outperformed the conventional dryer in terms of daily exergy efficiency by 34.3 to 85%. The highest exergy efficiency was found between 12:00 to 12:40 in all setups. The maximum exergy efficiency along with maximum solar radiation were 35.26% and 973 Wm^{-2}, 40.16% and 1011 Wm^{-2}, 36.5% and 1045 Wm^{-2}, 31.51% and 985.6 Wm^{-2}, 37.24% and 944 Wm^{-2}, 29.65% and 1022 Wm^{-2}, 34.07% and 1078 Wm^{-2}, 22.15% and 859.2 Wm^{-2} for Case_1 through 7 and conventional dryer, respectively. A 50 mm air gap performed better than a 100 mm air gap thickness when compared. Results showed that mass flow rate has a greater effect on energy efficiency than solar radiation. Additionally, the outcomes demonstrated that the exergy efficiency of SC is significantly influenced by the stack height and air gap thickness. An equation can be developed to relate the effect of SC stack height-to-air gap ratio on exergy efficiency. It was observed that the SAC's energy efficiency increased along with the increase in solar intensity as shown in Fig. 11. The highest energy efficiency coincided with the highest time of day for sunshine. This figure demonstrated that exergy efficiency rises linearly as solar radiation increases.

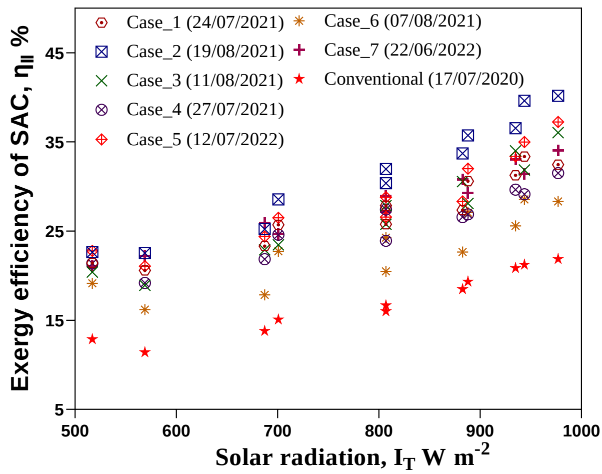


Fig. 11. Effect of solar radiation on exergy efficiency

3.3.4. Effect of solar chimney on drying temperature

During the trial periods, the ambient temperature and relative humidity varied from 21.5 to 35 °C and 35% to 63%, respectively. Fig. 12 shows the daily mean air temperature and relative humidity values for all settings inside the drying chamber. According to the figure, the conventional ISD's drying temperature ranged from 32.8 to 63.5 °C, whereas the novel ISD's ranged from 28 to 65 °C, with Case_2 configuration the highest record. This is because Case_2 obtained the highest useful heat gain from the SAC.

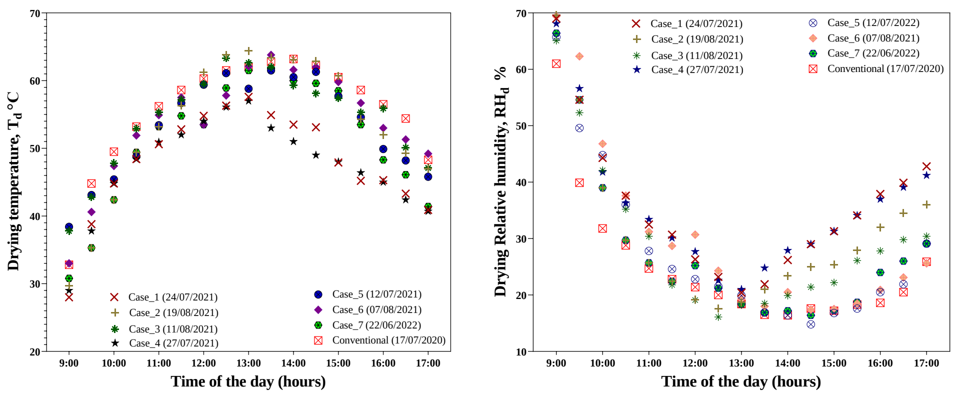


Fig. 12. Comparison of drying temperature and relative humidity inside drying chamber for different setups

For Cases_1 through 8, the average drying temperatures were 48.5, 54, 55, 48, 53.5, 54, 52, and 56 °C, with their corresponding relative humidity of 34.5, 29.5, 28, 35, 26.5, 29.5, 26.5, and 24%. Convectional dryer had an average drying temperature that was 4 °C higher than novel ISD since air flow rate of this dryer is low. The drying air temperatures under load are dropped by around 3.5 °C to 6 °C when compared to the drying temperature under no load conditions. The drop in temperature drying chamber was because of the product load. It was observed that the drying chamber's temperatures was roughly 19 to 27.5 °C higher than the ambient temperature during experimentation period. When air temperature is raised, the vapor pressure drops, resulting in less resistance to water evaporation. A SC with large stack height exhibited a higher RH, while a SC with a small stack height found a lower record.

3.3.5. Effect of type of solar chimney on moisture removal from product

After 8 hours drying period, the product's final weights for novel ISD of Case_1 through 7, conventional dryer and OSD were measured to be 199, 185, 205, 208, 182, 194, 197, 225, and 251 g, respectively from initial weight of 915 g with their corresponding moisture content of 33.8, 28.8, 35.7, 36.7, 27.6, 32.1, 33, 37, and 45.3% (w.b.), respectively. About 93.4% of the initial moisture content removed in Cases_2 and 5. A novel ISD with a 0.75 m stack height arrangement removed water from the sample more effectively than a conventional dryer and an OSD by about 3.85% and 8.75%, respectively. At the initial stages of drying (the first two hours of drying), drying was faster and at later stage, the apple slices need more time to remove the water trapped inside the pores of the sample. The effect of stack height and air gap thickness on moisture removal a two-way ANOVA performed in excel and the result was depicted in Table 3. The p-value for stack height is less than our significance level, this factor is statistically significant. On the other hand, the air gap thickness effect is not significant because its *P*-value (0.5598) is greater than our significance level which is Alpha = 0.05.

Table 3. Summary of statistical result

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Air gap	4.167	1	4.167	0.481	0.5598	18.513
Stack height	532	2	266	30.692	0.0316	19
Error	17.333	2	8.667			
Total	553.5	5				

3.3.6. Modelling of apple slices

Four mathematical model were identified for apple slices: Modified page, Midilli and Kucuk, Logarithmic and Verma et al. These models were used to evaluate to predict the moisture ratio (MR) obtained from the experimental data. In this research work, a novel dryer with a 0.75 m stack height and 100 mm air gap was selected to develop a mathematical model for apple slices. Conventional dryer and OSD were also modelled for comparison. Fig. 13 shows the moisture ratio versus drying time for both experimental and predicted value for novel, conventional and OSD, which represents the typical characteristic drying curve of apple slices during thin-layer drying operation.

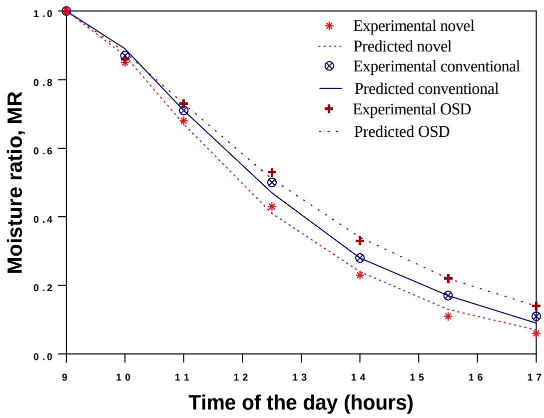


Fig. 13. Measured and predicted moisture ratio of apple slices

Table 4 presented the models parameters and the details of the statistical analysis of the four thin layer drying models for the novel ISD. It was found that Verma et al model gave better predicitions for moisture ratio of the apple slices than the other models.

Table 4. Parameters and statistical analysis for novel ISD

Model	**Model constants**	**RMSE**	χ^2	R^2
Modified page	k = 0.04135, n = 0.10508	0.06126	0.00525	0.96818
Midilli and Kucuk	k = 0.00104, n = 1.26796, a = 1.02604, b = 0.00012	0.02112	0.00105	0.99622
Logarithmic	k = 0.00464, a = 1.06298, c = 0.00021	0.05402	0.00511	0.97525
Verma et al	k = 0.00786, a = 3.81475, g = 0.001036	0.01334	0.00031	0.99849

3.3.7. Effect of type of solar chimney on energy consumption and drying efficiency

The specific energy consumption of a novel dryer consumed 6.78 MJ to 10.15 MJ of useful energy to remove 0.707 to 0.733 kg of water, whereas the conventional dryer required 4.96 MJ of energy to expel 0.690 kg of water during the same drying periods. However, it should be noted that bad weather conditions during the experiment also have effects in varying the results mentioned above. The effectiveness of energy consumption was found to be 2.50, 2.36, 2.47, 2.37, 2.81, 1.91, 2.64, and 1.46 kWh.kg^{-1}, for novel dryers (Case_1 to 7) and conventional dryer, respectively, with their corresponding drying efficiencies being 19.37, 20.4, 19.54, 20.51, 17.15, 25.25, 18.31, and 32.98%. This result indicated the effective utilization of energy by novel dryer than conventional dryer. Comparison between the novel dryer's setting, Case 5 had the highest energy usage (SEC), whereas Case 6 had the lowest. This outcome demonstrated the effect of mass flow rate on energy utilization. According to the findings, the novel dryer consumed between 22 to 53% more energy than that of conventional dryer. This is because dryers with highest energy efficiency use more energy than those with the lowest energy efficiency.

The drying efficiency values were similar for all SC configurations, with Case_6 showing a slight improvement. Case_4 exhibted higher drying efficiency than Case_1 and Case_7 while the lower values were obtained in Case_7 for the same SC height. The value of the drying efficiency a conventional dryer was estimated to be 8 to 16% more than the value obtained by the novel ISDs. It can be concluded that the amount energy supplied from collector to dried product is the parameter that affecting both drying efficiency and water removal from the product. The drying time can be reduced when more energy supplied to the product to be dried. Moreover, the drying efficincy rise by 38% when the SEC is reduced from 2.4 to 1.6 kWh kg^{-1}.

4. NEW SCIENTIFIC RESULTS

This section presents the new scientific findings from the research as follows:

1. *Correlation between the solar intensity on solar chimney and solar air collector surface, and ambient temperature*

Based on experimental results, I have developed a linear model to estimate relation between the amount of solar insolation received by solar chimney (SC) and solar air collector (SAC) surfaces in the operation range of 400 to 1000 Wm^{-2} and ambient temperature range from 18.7 to 37.4 °C for experimentally for the most applicable months: June, July, and August:

$$I_{SC} = 0.955\ I_{SAC} - 276.2,\ R^2 = 0.990, \text{ for June}$$

$$I_{SC} = 0.471\ I_{SAC} + 158,\ R^2 = 0.849, \text{ for July}$$

$$I_{SC} = 0.513\ I_{SAC} + 165,\ R^2 = 0.988, \text{ for August}$$

During the approximation the standard deviation was 17%, 10% and 14% for June, July, and August, respectively.

Additionally, I have developed a correlation between the intensity on SAC and the ambient temperature (T_a) for each month:

$$T_a = 0.018\ I_{SAC} + 12.1,\ R^2 = 0.785 \text{ for June}$$

$$T_a = 0.020\ I_{SAC} + 12.5,\ R^2 = 0.859 \text{ for July}$$

$$T_a = 0.014\ I_{SAC} + 15.1,\ R^2 = 0.881 \text{ for August}$$

During the approximation the standard deviation was 8%, 8% and 8.9% for June, July and August, respectively. I have pointed out that the effect of SC on the dryer performance is ineffective when the intensity of solar radiation is below a certain threshold (200 $W.m^{-2}$).

Any location with a comparable climate can used these models.

2. *Effect of solar chimney type on air flow rate and collector temperature rise*

According to experimental results, I justified the increase of air flow rate ($\dot{m}_a$) with increase in solar radiation. For that purpose, I have developed a linear model to approximate the airflow rate and SAC outlet air temperature for solar radiation intensity range of 500 $W.m^{-2}$ and 950 $W.m^{-2}$.

$$\dot{m}_a = 0.535 + 0.00163\ 10^{-2}\ I_{Tc}.$$

The correlation coefficient was 0.95 along with standard deviation of 0.118 kg s^{-1}.

Additionally, I have developed a linear model to estimate SAC's outlet air temperature ($T_{c,o}$) in terms of solar radiation intensity for a range between 500 $W.m^{-2}$ and 950 $W.m^{-2}$ and inlet air temperature range from 19.8 to 36.4 °C.

$$T_{c,o} = 29.3 + 0.0487 \cdot I_{Tc}.$$

The correlation coefficient was 0.96 along with standard deviation of 2.014 °C. I have proved that raising the stack height from 0.5 m to 1 m resulted in a 31% increase in airflow rate and a 3.7 °C decrease in temperature rise. Moreover, I have proven that the air gap does not have any significant correlation with SAC outlet temperature with stack height beyond 1 m.

3. Impact of solar chimney type on collector performance

I have pointed out that the SC stack height and air gap thickness have a significant impact on the energy and exergy efficiency of the SAC, and so based on the experimental findings and chimney height-to-gap ratio (H_{ch}/t_{ch}), I have developed a second order polynomial model in order to approximate the relation between the energy (η_I) and exergy (η_{II}) efficiency of the SAC versus the SC stack height-to gap ratio:

$$\eta_I = -0.1785\left(\frac{H_{ch}}{t_{ch}}\right)^2 + 5.124\left(\frac{H_{ch}}{t_{ch}}\right) + 62.80, \quad R^2 = 0.8912$$

$$\eta_{II} = -0.0875\left(\frac{H_{ch}}{t_{ch}}\right)^2 + 2.481\left(\frac{H_{ch}}{t_{ch}}\right) + 13.52, \quad R^2 = 0.8654$$

The regression model's plausible range for the energy and exergy efficiencies falls between 45.5% to 70% and 20% to 35% with the corresponding SC's stack height and air gap thickness within the ranges of 0.5 m to 1 m, and 50 mm to 100 mm respectively.

Comparing air gap thickness, I justified a SC with a 50 mm air gap thickness outperformed with a 100 mm air gap, a 13% boost in performance for solar radiation range of 500 $W.m^{-2}$ to 950 $W.m^{-2}$.

4. Moisture removal of apple slices

I have evaluated and justified the integration of a solar chimney on improving the solar drying process in terms of moisture removal from the product to be dried. I have determined that after 8 hours drying period about 93.4% of the product's initial moisture content removed when using a SC stack height of 0.75 m and an air gap of 50 and 100 mm.

Based on experimental results, I have proven the Verma et al. model found to best explain thin layer drying behavior of apple slices (Golden Delicious) as compared to other models for an initial moisture content of 85.6 % (w.b.) and apple thickness of 4 mm:

$$MR = a\,exp(-kt) + (1-a)\,exp(-gt).$$

The identified model parameters are k = 0.00786, a = 3.81475 and g = 0.00104 and the coefficient of determination was 0.9985.

5. Energy consumption and drying efficiency

I have justified that the quantity of total useful heat gain suppled from the solar collector determines the amount of energy required to remove moisture from the drying product and drying efficiency. I have proven that in terms of specific energy consumption (SEC), a novel solar dryer utilized between 22 and 53% more energy to remove 1 kg of dried product’s moisture than a conventional dryer. I have elaborated that the drying efficiency rise by 38% when the SEC is reduced from 2.4 to 1.6 kWh kg^{-1}.

Additionally, I have pointed out that the quantity of SEC is dependent on the amount of moisture remaining in the product to be dried, with low moisture content requiring more SEC.

Based on the experimental findings, I have also pointed out that both stack height and air gap have a considerable impact on energy consumption for removal of moisture from the product.

5. CONCLUSION AND SUGGESTIONS

In conclusion, an experimental evaluation has been conducted to determine the performance of a novel natural indirect type solar dryer (ISD) using different solar chimney designs under no-load and load conditions. In this research work, the effect of solar chimney types has been evaluated by comparison between different SC stack heights and air gap thicknesses. Additionally, conventional dryer and OSD were also tested for comparison purposes. During the experimental periods, the range of solar radiation and ambient temperature were between 213 to 1083 W.m^{-2} and 18 to 37 °C with their corresponding average value of 751 W.m^{-2} and 30 °C, respectively. It had been found that the solar chimney has no effect when the solar radiation intensity below 200 W.m^{-2}.

The no-load performance evaluation of the novel ISDs is crucial to understand the extent of the maximum temperature achieved by the ISD. Under-load evaluation, it was found that the SAC outlet temperature raised above the ambient temperature by about 5 °C at low radiation and reached 20 °C at higher radiation.

Under product load conditions, the collector temperature change was found to be higher by about 1 to 4 °C when using an air gap of 50 mm. The drying air temperature under load conditions was lower than a drying temperature under no load conditions because of the presence of product in case of under load conditions.

On energy and exergy efficiency analysis, a SC configuration with a 0.75 m and 50 mm air gap outperformed. A SC with non-uniform airgap worked better than the other air gaps with the same stack height. Increasing SC height up to a definite point and a decreasing air gap were favourable.

Based on moisture removal, energy utilization and drying efficiency, a 0.75 m stack height with 100 mm air gap solar chimney was the best configuration where the highest drying efficiency, lowest energy consumption (SEC) and more moisture removed obtained by this configuration.

The study's experience has shown that conducting an experiment to determine the impact of all pertinent parameters would be time-consuming. Specific aspects need to be scrutinized in future experimental activities. The next step should be analytical modelling and CFD simulations utilizing actual inputs like those given in this paper, in order to understand how the dryers, operate under various circumstances. Such a technique would make it easier to identify areas that required additional testing, enhancing dryer designs.

6. SUMMARY

PERFORMANCE EVALUATION OF SOLAR CHIMNEY APPLIED FOR DRYING PROCESSES

A comprehensive experimental evaluation of the performance of a novel indirect type of natural convection solar dryer (ISD) for drying applications has been conducted under the climatic conditions of Gödöllő, Hungary (47° 35' 39" N and 19º 21' 59" E). The novel dryer consists of three primary components: a single-pass solar air collector, a drying chamber, and a solar chimney (SC). To achieve the aim of the research, three SC stack height (0.5, 0.75 and 1 m) and three air gap thicknesses (50 mm, 100 mm, and non-uniform gap) were selected. In addition, conventional dryer and OSD were tested for comparison purposes. Therefore, a total of 17 experiments have been carried out in this study. Parameters utilized to evaluate and compare the proposed novel ISDs were energy and exergy (2E) analysis, product moisture loss, drying efficiency and specific energy consumption (SEC).

The SAC temperature difference between inlet and outlet of an air gap of 50 mm greater than 1 to 4 °C when compared to a 100 mm air gap. It was found that as the SC height increased from 0.5 m to 1 m, the air flow rate increased by 31%, while the temperature reduced by 3.7 °C. The novel ISD's thermal and exergy efficiencies of SAC increased by 31.8 to 82% and 48.5 to 87%, respectively, as compared to the conventional ISD. The daily total useful heat gained by the novel ISDs and conventional ISD ranged from 1.1 to 2.26 kWh. It was also found that a SC set up with a non-uniform air gap thickness of performed better when compared to SC with 50 mm and 100 mm air gap thickness of 1 m stack height.

The drying air temperatures under load conditions have been found to be between 3.5 °C to 6 °C lower than the drying temperatures under no load conditions. Statistical results showed that SC stack height has a significant effect on product moisture loss than SC air gaps. After 8 hours drying period, about 93.4% of the product's initial moisture content removed when using a SC stack height of 0.75 m and an air gap of 50 and 100 mm. However, the amount of energy required to remove the moisture from the product was higher. The novel dryer consumed 0.45 to 1.35 kWh more energy (SEC) to dry 1 kg of dried product than conventional dryer. Moreover, there was no considerable differences on SEC and drying efficiency for SC stack heights and air gap thickness, except for a 0.5 m SC stack height.

Verma et al. model found to best explain thin layer drying behavior of apple slices (Golden Delicious). The best configuration, according to the study, was a SC with 0.75 m stack height and a 50 mm air gap thickness.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Refereed papers in foreign languages:

1. **Habtay, G.,** Buzas, J., Farkas, I. (2019): Mathematical modelling of cylindrical chimney effect in solar dyer, Hungarian Agricultural Engineering, No. 36/2019, pp. 69-74. *https://doi.org/10.17676/HAE.2019.36.69*
2. **Habtay, G.,** Buzas, J., Farkas, I. (2020): Heat transfer analysis in the chimney of indirect solar dryer under natural convection mode, FME Transactions, 48(3), pp. 701-706. *https://doi.org/10.5937/fme2003701H* (Scopus: Q2)
3. **Habtay, G**., Al-Neama, M.A., Buzas, J., and Farkas, I. (2021): Experimental performance of solar air collectors for drying applications. European Journal of Energy Research, 1(5), pp. 4-10. *https://doi.org/10.24018/ejenergy.2021.1.5.29*
4. **Habtay, G.**, Buzas, J., Farkas, I. (2021): Performance evaluation of solar air collector by chimney effect for drying applications. Acta Technologica Agriculturae, 24(4), pp.159-165. *https://doi.org/10.2478/ata-2021-0027*
5. Dhaundiyal, A., **Habtay, G**. (2022): The effect of psychrometry on the performance of a solar collector. Environmental Science and Pollution Research, 29(9), pp. 13445–13458. *https://doi.org/10.1007/s11356-021-16353-5* (Scopus: Q2, IF = 4.223).
6. **Habtay, G.**, Buzas, J., Farkas, I. (2022): Comparative study on the performance of solar dryer with finned plate solar chimney. Jurnal Tekno Insentif, 16(1), pp. 1–15. *https://doi.org/10.36787/jti.v16i1.453*

Refereed papers in Hungarian language:

7. Buzás, J., **Habtay, G.,** Farkas, I. (2021): Napenergiás kéményes szárító hőtechnikai vizsgálata, Energiagazdálkodás, 62. évf., 2-3. sz., 2021, 18-22. o. ISSN 0021-0757