DESIGN, DEVELOPMENT AND NUMERICAL CHARACTERIZATION OF INDIRECT DOMES-TIC HYBRID SOLAR DRYER

Thesis submitted in fulfilment of the requirements for the Degree of

Doctor of Philosophy

By

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DECLARATION BY THE SCHOLAR

I hereby declare that the work reported in the Ph.D. thesis entitled "DESIGN, DEVELOPMENT AND NUMERICAL CHARACTERIZATION OF INDIRECT DOMESTIC HYBRID SOLAR DRYER" submitted at Bennett University, Greater Noida, India, is an authentic record of my work carried out under the supervision of Dr. Deepali Atheaya and Dr. Anil Kumar. I have not submitted this work elsewhere for any other degree or diploma. I am fully responsible for the contents of my Ph.D. Thesis.

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SUPERVISOR'S CERTIFICATE

This is to certify that the work reported in the Ph.D. thesis entitled "DESIGN, DEVELOPMENT AND NUMERICAL CHARACTERIZATION OF INDIRECT DOMESTIC HYBRID SOLAR DRYER" submitted by Mukul Sharma at Bennett University, Greater Noida, India, for the award of the degree of Doctor of Philosophy (Ph.D.), is a bonafide record of his / her original work carried out under my supervision. This work has not been submitted elsewhere for any other degree or diploma.

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(MUKUL SHARMA)

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LIST OF ACRONYMS AND ABBREVIATIONS

2D	Two- dimensional
3D	Three- dimensional
ASTM	American Society of Testing and Materials
CFD	Computational fluid dynamics
СОР	Coefficient of performance
EPBT	Energy payback time
FRP	Fiber reinforced plastic
GI	Galvanised iron
GHG	Greenhouse gases
HUF	Heat utilisation factor
IP	Improvement potential
ITDHSD	Indirect type domestic hybrid solar dryer
МТ	Million Tonnes
РСМ	Phase change material
PV	Photovoltaic
Κ	Kelvin
SI	Sustainability index
Wb	Wet bulb
WER	Waste exergy ratio

LIST OF SYMBOLS

Ι	solar insolation (in W/m ²)
T_S	maximum stagnation temperature (in K)
T_a	ambient temperature (in K)
E	fluid's total energy (in J)
v	fluid velocity (in m/s)
s _n	the direction vector of the sun
r	position vector
a_s	coefficient of absorption
s'	scattering direction vector
n	refractive index
T _{sc}	temperature inside the solar collector
T_{dc}	temperature inside drying cabinet
'n	mass flow rate of air
Rha	ambient relative humidity (in %)
Vair	velocity of inlet air (in m/s)
Idirect	direct solar insolation (in W/m ²)
Iglobal	global solar insolation (in W/m ²)
Т	local temperature (in K)
A_{sp}	area of the side panels of the cabinet in m^2
A _b	area of the base of the cabinet in m^2
Ag	area of the transparent cover of the cabinet in m^2
q_{sp}	heat loss from side panels
qь	heat loss from bottom
q_{g}	heat loss from top glazing

x thickness of cabinet side panels in m

- \mathbf{X} thickness of insulation in bottom of solar collector in m
- k thermal conductivity of FRP side panels
- K thermal conductivity of glasswool
- ε emissivity of surfaces
- hg convective heat transfer coefficient of above glazing
- h_r radiative heat transfer coefficient from glazing
- T_{ab} temperature of absorber
- T_a ambient temperature
- T_{g} temperature at top of glazing
- I_g global solar insolation
- M_t instantaneous moisture content at any time 't'
- W_t crop weight at any time 't'
- W_{dry} weight of dried crop
- W_{total} total weight of crop
 - M_e equivalent moisture content in the crop
 - M_i initial moisture content of the crop
 - *RH* relative humidity
 - *R* universal gas constant
- $T_{absolute}$ absolute temperature
 - D_r drying rate
- M_{final} final moisture content of the crop
 - t total Time duration
 - M_w moisture evaporated from the crop
 - l_w latent heat of vaporisation for water
 - I_{sc} global solar insolation on the solar collector
 - A_{sc} area of solar collector

t _i	time interval
$\dot{m_a}$	mass flow rate of air
c _{pa}	specific heat capacity of air
Т	air Temperature
T_a	ambient air temperature
T _{sc}	temperature of air at outlet of solar collector
T_{dc}	temperature of air at outlet of drying cabinet
η_{PV}	efficiency of PV module
I_{PV}	incident solar insolation on PV module
A_{PV}	area of PV module
I _{sc}	short circuit current
Voc	open circuit voltage
I_L	load current
V_L	load voltage
A _{sc}	area of solar collector (m ²)
c_{pa}	specific heat capacity of air
I_g	solar insolation (W/m ²)
V	fluid velocity (in m/s)
<i>s</i> _n	the direction vector of the sun
r	position vector
a_s	coefficient of absorption
s'	scattering direction vector
'n	mass flow rate (kg/s)
n	refractive index
T_{dc}	average drying temperature (K)
T_{do}	dryer outlet temperature (K)

- T_i collector inlet temperature (K)
- T_{sc} collector outlet temperature (K)
- ρ_s fluid density (in kg/m³)
- au transmissivity
- α_s absorptivity
- σ_s scattering coefficient
- $\sigma \qquad Stefan-Boltzmann\ constant\ (in\ W/m^2K^4)$
- ϕ phase function
- Ω' solid angle (in Steradian)

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ABSTRACT

A novel design of domestic hybrid solar dryer system has been proposed and analysed with Computational Fluid Dynamics (CFD) using Ansys Fluent 19.2 software under unload condition. Further, Experiments under unload and load conditions were performed at Delhi Technological University (DTU), Delhi in the month of November 2021. From unload experimentation, thermal performance parameters namely thermal efficiency, HUF (heat utilisation factor) and COP (coefficient of performance) of solar collector in indirect type domestic hybrid solar dryer were evaluated. The maximum values of thermal efficiency, HUF, and COP were noted as 59%, 0.68, and 0.32 at 13:00 hours. The theoretical results were in fair agreement with experimental results as evaluated using linear regression analysis. Moreover, ITDHSD (indirect type domestic hybrid solar dryer) was found superior to other developed solar dryers in terms of maximum collector thermal efficiency.

From experiments under load condition, various parameters such as thermal performance, exergy and drying kinetics of tomato slices were analysed. Moisture in tomato slices was dried from 95% to 9% (wet basis) in 10 hours of solar drying in ITDHSD during the winter season. Drying curve obtained was fitted with different existing empirical models and Prakash and Kumar model was found suitable for tomato drying in ITDHSD. Overall drying efficiency of the system was estimated as 41.05%. Furthermore, exergy efficiency values varied from 32.86% to 58.26% with variable mass flow rate. Overall exergy efficiency was 46% during tomato drying experimentation. Various exergy sustainability indicators have been estimated in this research work and the primary aim was to observe improvement potential in the system. Improvement potential, waste exergy ratio and sustainability index of the ITDHSD system were estimated in the range of 0.006966 - 0.065984, 0.41 - 0.67, and 1.55 - 2.39, respectively.

Furthermore, environmental, economical, and quality parameters for drying tomato flakes were evaluated for ITDHSD system. Embodied energy during dryer fabrication was estimated as 1434.176 kWh. Energy payback time, total CO₂ mitigation, and earned carbon credit for tomato drying in dryer were projected as 4.21 years, 12.28 Tonnes, and \$364. Initial capital cost for drying system fabrication was

\$245. The drying system can pay back all initial costs in 6 months of operation as estimated for tomato flakes drying. Moreover, quality of dried tomato flakes in dryer and open sun drying was estimated and compared. Indirect type domestic hybrid solar dryer provided better quality dried tomato flakes than open sun drying method as estimated from sensory analysis, rehydration ratio, shrinkage and hardness test.

Moreover, a unique sinusoidal corrugated solar collector was also designed and proposed to improve performance of ITDHSD system. The design was created using Ansys Spaceclaim 2022 version R2 software and further simulated using Ansys Fluent 2022 version R2 software. Mass flow rate for the dryer system was optimised and inlet velocity of 0.6 m/s (0.0221 kg/sec) was found appropriate for crop drying. While performing simulation input parameters such as ambient air temperature, solar insolation etc. for the winter season were used for the analysis. It was observed that collector will provide better results and average drying temperature of 324 K - 332 K was noted when solar insolation was varied in a range of 500 W/m² to 1000 W/m². ITDHSD system embedded with sinusoidal corrugated thermal collector can provide better drying and wide variety of crops can be dried in the developed dryer.

Indirect type domestic hybrid solar dryer (ITDHSD) had potential to provide an economical, efficient, and environmentally friendly alternative to traditional drying methods. The results demonstrate that the ITDHSD system can help to reduce energy consumption, greenhouse gas emissions, and improve the quality of dried products, making it an attractive option for domestic users as well as smallscale agricultural producers. The findings of this study can provide useful insights for designing and implementing sustainable and cost-effective drying systems for other food products.

Keywords: Domestic; Indirect; Thermal performance; Tomato; Embodied; Exergy; Sinusoidal corrugation

CHAPTER-I

INTRODUCTION AND LITERATURE REVIEW

1.1. General Introduction

For centuries, fossil fuels have been the main source of energy. These are accessible all around the world in large quantity. Since the world has been utilising fossil fuels for so long, the technology for extracting energy from them is quite advanced [1]. For domestic users and farmers, fossil fuels provide a steady and affordable source of energy. In order to meet the requirements of the entire planet, fossil fuels have been an amazing source of energy. Fossil fuel supplies have been depleting, and it is impossible to renew them [2]. Therefore, excessive usage of non-renewable resources will prevent them from being available to future generations.

Uncapped use of fossil fuels damages the ecosystem because they cause air pollution through production of harmful gases including CO₂, NO₂, and SO₂ [3]. The extraction of fossil fuels results in deadly illnesses among those who work there [4]. The globe is dealing with an energy crisis, which affects both developed and developing nations. It is common scenario that the supply of fossil fuels is extremely constrained, and that demand for oil and natural gas is rising globally as their stock is steadily depleting [5]. Even still, power is often unavailable or, if it is, it is either too expensive or unreliable for farmers and small-scale industries in many parts of developing countries [6], [7]. Another obstacle for farmers to operate their farm equipment is the enormous cost of fossil fuels.

Another demerit of using fossil fuels is that average world temperature rises as fossil fuel emissions continue to rise. According to the UN Inter-Governmental Panel on Climate Change (IPCC), due to atmospheric pollution, the mean earth temperature will rise by about 1.5 ^oC in the following 60 to 80 years [8]. These causes are triggering global warming to have a negative impact on people, the environment, and the entire planet [9]. As a result, the sea level is rising, precipitation and snow/ice melting rates are changing, the geographical distribution of species is altering, and many plant and animal species are in danger of going extinct. The impact of greenhouse gases on the ecosystem and weather systems has become more apparent over time. As a result, while some areas experience drought, others receive more rain [10]. While comparing renewable energy sources with fossil fuels, the former is more reliable and promising in the long run. Solar and other

renewable energy sources are far more beneficial, dependable, cost-effective, and environmentally friendly than fossil fuels [11].

Utilisation of solar energy as a dependable and sustainable source of energy has grown much more quickly. In India, there has been a significant increase in energy usage and development of projects to produce electricity from renewable sources [12]. Compared to traditional fossil fuel sources, renewable energy sources are far more cost-effective [13]. In order to meet the nation's energy needs, renewable energy sources are the most readily available, affordable, clean, and ecologically beneficial options. India is making good strides towards using renewable energy sources as its primary energy source, and there are good prospects that it will eventually become an energy-efficient nation [14], [15].

A significant problem facing the world is the loss of consumable food. The situation is particularly severe for developing nations because a sizable portion of consumable food is wasted owing to pest damage, degradation, and careless handling [16], [17]. According to studies, food production in the nation and the rest of the world has somewhat increased during the past ten years. India's total crop production in 2012–13 was roughly 257 million tonnes, and it has since climbed to 316.06 million tonnes in 2021-22, placing it as the second greatest producer of food in the world [18]. However, this information pertains to India, the second-largest nation in the world by population. Food grains and agricultural goods are insufficient to ensure the rising population has access to a healthy diet [19].

Each year, a sizable number of crops grown worldwide that are intended for human use are lost or damaged. This amount equals almost 1.3 billion tonnes annually. From the point of cultivation to the market level, there are 10% post-harvest losses of food grains in India, accounting for around 5% of the market for distribution [20]. Assume that achieving food security goals requires sustainability. Food availability must be increased for this, and post-harvest losses from the field to the consumer must be decreased. In recent years, there has been a noticeable increase in food production, and much focus has been dedicated to allocating resources towards improving agricultural productivity. For instance, over the past three decades, research expenditures have increased to 95% with an emphasis on improving food production and lowering losses by up to 5% [21]–[23]. Therefore, it becomes clear that there are only two options for boosting dietary grain:

- i. More total farmed land.
- ii. Increased food production and preventing post-harvest losses.

The loss of food grains makes up 10% of the total food production losses. According to a study, thorough preventive measures can cut the annual loss of food grains by around 10%, or about 20 MT, saving between 350 and 400 billion. These solutions may include appropriate management and adequate storage options spread across the nation [24], [25].

India produces the second-largest amount of food grains in the world, and despite the green revolution, there is now insufficient food and nutrition for country's expanding population. Despite the enormous production, India has poor per capita availability due to the large population and significant food product losses during processing. Food grain production in India is shown in Figure 1.1 from 2015–16 to 2021–22 [26]. It displays an ongoing rise in food grain produce.



Foodgrain production over the years - Output (in MT)

Figure 1.1. Food grain production from 2012-13 to 2021-22 in India [26]

The post-harvesting process starts from the instant the crop is harvested from the field. The post-harvest technology maintains and extends the shelf life of crops and results in food loss reduction. The post-harvest process comprises four stages, viz. sorting, drying, storing, packaging and transporting the harvested crop to the nearest market [27], [28]. The post-harvest system's operations and activities can be divided into two categories:

- I. Technical tasks include cultivation, harvesting, cutting and threshing, drying, cleaning, final drying, processing, and storing.
- II. Economic activities: management and administration of all general tasks such as crop quality and nutrition maintenance, transportation, and marketing.

Post-harvest crop drying is an essential activity that can increase the shelf life of a crop. This activity has been prevalent among people living in South Asian countries since the ancient era [22], [29]. For crop storage for an extended period, the drying activity is performed. In ancient agriculture practices, the food crop was dried using the sun's radiation in an open environment. This method is known as open sun drying method. This process has several disadvantages like deterioration of food due to climate, dust, animals, birds, and micro-organisms [22], [30]. Also, this method is time-consuming. Various devices are developed for food drying in modern agricultural practices, that run over conventional and non-conventional energy, preferably solar energy. These devices are known as food dryers.

The food dried using these dryers has similar properties viz. colour, texture, and taste as the original undried food. Several foods such as grains, fruits, leafy vegetables, fish, and various seafood are dried and stored for more extended period using a drying process [31]. If electrical and mechanical equipment is utilised to dry food, it can be expensive and an energy-intensive operation. The primary cause that led to the replacement of this traditional technology for food drying with more affordable alternatives is electricity prices. Different types of solar dryers to get around this issue have been developed by researchers which are more economical than conventional dryers and efficient than traditional open sun drying method. These solar dryers are divided into three different types: direct type, indirect type, and mixed

type [32]. Based on their operation, these dryers can also be split into two categories: active type dryers (forced convection) and passive type dryers (natural convection) [33]. Figure 1.2 depicts the classification of solar drying.



Figure 1.2. Classification of solar drying

1.1.1. Types of solar dryers

Solar dryers are mainly classified into three types viz. direct, indirect and mixed type but some innovative dryers are also considered as hybrid type of solar dryers. These types of solar dryers have been discussed further in detail.

1.1.1.1.Direct type solar dryers

Direct solar radiation is used in direct type solar dryers for food drying. Around the world, these two well-known dryer kinds are in use. The first is a cabinet-style dryer, and the second is a greenhouse dryer [34], [35]. These dryers are economical, and the fabrication processes are simple. The materials required for fabrication are readily available locally. Both dryers can operate in active and passive modes of heat transmission. Direct type solar dryers' interior temperature ranges from 45 to 70 degrees Celsius, and their extremely low relative humidity levels (less than 50%), make them best suited for low level thermal drying [7], [36]. Figure 1.3 shows working of a direct type solar dryer. Direct type solar dryers offer various advantages and disadvantages, which are summarized below [6], [31], [36]:

Advantages:

- Simplicity: Direct solar dryers are easy to install and maintain because of their straightforward design and construction. They consist of a single chamber that is exposed to direct sunlight, which simplifies their construction.
- Cost-Effectiveness: Direct solar dryers are typically less expensive to construct and run than other drying systems because of their simplicity. Typically, they demand less money to spend on technology and supplies.
- Environmentally beneficial: Since direct solar dryers only use energy from the sun, they are both sustainable and environmentally beneficial. They don't contribute to air pollution or the production of greenhouse gas emissions.
- Energy Efficiency: Direct solar dryers can draw their energy for free and in large quantities from the sun. As a result, they are inexpensive to operate and can work well in areas with lots of sunlight.
- Preservation of Nutrients: Direct solar drying often uses less force than other drying techniques, such as traditional hot air drying. The original flavours and nutrients in the dried food products can preserved as a result.

Disadvantages:

- Direct solar dryer effectiveness is heavily influenced by weather, particularly the amount of sunshine available. The drying process might be slowed down or even completely stopped by cloudy days or unfavourable weather.
- Longer Drying Time: In comparison to traditional drying techniques like hot air drying, direct solar dryers often have longer drying times. This prolonged drying period may be a drawback, particularly for goods that are moisture-sensitive or perishable.
- Limited Drying Capacity: Direct solar dryers may have a limited drying capacity due to their single-chamber design, which makes them unsuitable for extensive drying operations.

- Inconsistent Drying: Direct sun dryers may produce inconsistent drying results if temperature and humidity are not precisely controlled. This can have an impact on the dried goods' quality and shelf life.
- Contamination Risk: Because direct sun dryers are frequently exposed to the outdoors, there is a chance that dust, insects, or other outside elements could contaminate the process.

Direct-type solar dryers are simple, cost-effective, and environmentally friendly. They are, however, weather-dependent, have lengthier drying durations, and their drying capacity and control may be limited. The drying method used should take into account the specific needs and restrictions of the drying process, as well as the desired quality of the dried items.



Figure 1.3. Schematic diagram showing working of direct type solar dryer [37]

1.1.1.2.Indirect type solar dryer

These solar dryers harness solar radiations using solar collector and dry food by virtue of convection. The food item is housed in a separate container known as the

drying chamber in indirect type solar dryer. The solar collector utilises the sun's rays to capture heat when it is positioned beneath direct sunlight exposure. Using air as a medium, this heat is subsequently transmitted to the drying chamber. The food in the drying chamber is successfully dried as the air comes into touch with the food products there and draws moisture out of them. These indirect type solar dryers provide a range of operational options. Depending on how moist the crops are to be dried, both active and passive modes can be used [22], [31], [36]. While active indirect solar dryers are made to handle crops with higher moisture levels, passive indirect solar dryers are appropriate for crops with low moisture content. Indirect type solar dryers also come with their own set of advantages and disadvantages [31], [32], [36]:

Advantages:

- Increased Efficiency: Compared to direct sun dryers, indirect solar dryers often have a higher drying efficiency. They can obtain higher and more reliable dry-ing temperatures by using an air heating collector, which shortens the drying process.
- Weather Independence: Indirect solar dryers are less reliant on the weather than direct sun dryers. Even on overcast or less sunny days, using the air heating collector enables more precise and uniform drying.
- Improved Drying Control: Indirect sun dryers offer improved temperature and humidity control as well as better control over the drying process. This control results in more consistent and superior dried goods.
- Greater Drying Capacity: Indirect sun dryers are excellent for industrial and commercial drying applications since they can be built with more drying chambers or a greater capacity.
- Reduced Risk of Contamination: In indirect sun dryers, the closed design of the drying chamber helps to shield the food products from external contaminants like dust, insects, or pollution.

Disadvantages:

- Higher Complexity: Compared to direct sun dryers, indirect solar dryers typically have more intricate designs. They need extra parts, such as fans and air heating collectors, which might raise the initial cost and maintenance expenses.
- Energy Consumption: Especially in active indirect sun dryers, the usage of fans and air heating collectors may result in some energy consumption. Although they still use less energy than traditional drying techniques, they might not be dependent on solar energy.
- Technical expertise: Installing, operating, and maintaining indirect solar dryers properly may require specialised technical expertise, which may be difficult for some users.
- Potential for Overheating: In indirect solar dryers, there is a chance of the drying chamber becoming too hot if the temperature is not carefully maintained. This will result in the loss of nutrients and lower the overall quality of the dried goods.

Indirect type solar dryers offer more capacity, increased efficiency, and controlled drying. It may, however, be more difficult and need for greater upfront costs as well as technical understanding. The exact drying requirements, the resources at hand, and the size of the drying operation should all be taken into account when deciding between direct and indirect solar dryers.



Figure 1.4. Indirect type solar dryer [36]

1.1.1.3.Mixed type solar dryer

To increase efficiency, mixed mode solar dryers combine direct and indirect drying methods. The drying time of these dryers is drastically shortened since they use solar air heating collectors to heat the food products while also using direct sunshine exposure. The drying chamber of these dryers is placed in a manner that will allow it to receive direct sunshine radiation [11], [38], [39]. Convection is used to transport solar thermal energy to the air inside the chamber, either by forced or passive convection. The drying process is maximised by this cutting-edge setup of direct solar exposure and solar air heating collector, making it quicker and more efficient. The properties of both direct and indirect solar dryers are combined in mixed mode solar dryers, which presents a distinct combination of benefits and drawbacks [11], [36], [40]:

- Faster Drying: Compared to conventional direct solar dryers, mixed mode solar dryers can considerably shorten the drying time by utilising both direct sunshine exposure and a solar air heating collector. The drying process is made more effective overall by combining these two techniques.
- Improved Efficiency: By combining the ideas of direct and indirect drying, efficiency is increased overall, and solar energy is used more effectively. Dried goods may become more consistent and of greater quality due to increased efficiency.
- Versatility: Mixed mode solar dryers can be used in a variety of climates. On clear days, they can switch to the indirect mode and use the solar air heating collector for a more regulated drying process. On bright days, they can rely more on direct solar radiation.
- Better Control: The mixed mode design gives the drying chamber's temperature and humidity levels more flexibility. It reduces the possibility of over-drying or overheating while also promoting uniform drying.
- Moderate Complexity: Mixed mode solar dryers are less complex than pure indirect dryers, yet they are more complex than direct solar dryers. These dryers successfully balance simplicity and effectiveness.

Disadvantages:

- Initial Cost: When compared to direct solar dryers, the initial cost of installing a mixed mode solar dryer may be greater. Increased investment is a result of the additional components needed, such as the control systems and solar air heating collector.
- Technology: For effective installation, operation, and maintenance, mixed mode solar dryers may need some technical know-how, particularly if they are active mixed mode dryers.
- Energy Consumption (for Active Dryers): When fans or blowers are employed to circulate air in active mixed mode solar dryers, there is some energy consumption involved. This should be taken into account when striving for complete reliance on solar energy, even if they are still more energy-efficient than traditional dryers.
- Complexity of Passive Systems: Some passive mixed mode solar dryers circulate air naturally through convection. It can be difficult to create an effective passive mixed mode dryer since heat distribution and airflow must be balanced.
- Room Requirement: The setup of the numerous components for the integration of both direct and indirect drying systems may demand additional room, which could be a problem in some situations.

Mixed mode type solar dryers enable drying that is quicker, more effective, and more precisely controlled. However, depending on the particular design, they can need a bigger upfront expenditure and some technical know-how. When selecting a mixed mode solar dryer, it is important to take into account the drying requirements, the resources at hand, and the required level of control.


Figure 1.5. Mixed type solar dryer [41]

1.1.1.4.Hybrid solar dryers

Modern drying systems called hybrid solar dryers, combine solar energy with energy from various sources to maximise the drying process. To assure constant and effective drying regardless of the weather or time of day, they combine solar energy with electricity, biomass, or other traditional energy sources [42]–[44]. The hybrid strategy combines the benefits of a reliable backup energy supply with those of green solar energy. Advantages and disadvantages of hybrid solar dryers is mentioned below [31], [44], [45]:

Advantages

- Continuous Drying: The addition of a backup energy source guarantees that drying will continue even when there is little or no sunshine available or when it is dark outside. It is particularly important for industries that demand consistent production.
- Enhanced Efficiency: When solar energy alone is insufficient, hybrid solar dryers can maintain a greater degree of efficiency by seamlessly transitioning to the backup energy source. Reduced drying times and improved performance are the results of this factor.

- Versatility: Hybrid solar dryers provide operational flexibility. When conditions allow, they can operate purely on solar energy, which lowers operating expenses and has a smaller negative impact on the environment. When necessary, the backup energy source is used, providing a flexible and dynamic drying solution.
- Reliability: The backup energy source guarantees the dependability of drying operations, lowering the possibility of disruptions or delays brought on by unfavourable weather.
- Energy Optimisation: Hybrid solar dryers can maximise the use of available resources by mixing solar energy with additional energy sources. This increases energy efficiency and lowers overall energy usage.

Disadvantages

- Higher Initial Investment: Compared to typical solar dryers, the integration of several energy sources and advanced control systems may result in higher initial setup expenses.
- Complexity: Compared to basic solar dryers, hybrid solar dryers can be more difficult to build and operate, necessitating knowledge of both solar energy systems and backup energy technologies.
- Hybrid solar dryers may need more frequent maintenance and technical support because there are more parts and systems involved, which will raise the cost of operation.
- Environmental Impact: Although hybrid solar dryers continue to be more environmentally friendly than traditional drying techniques, depending on the backup energy source used, there may be a small amount of greenhouse gas emissions.
- Dependence on Backup Energy: Although the backup energy source guarantees continuous drying, it could result in dependence on non-renewable energy sources, lowering the drying process's overall sustainability.

Hybrid solar dryers combine the advantages of solar energy with backup energy sources to provide a flexible and effective drying solution. They offer continuous drying and improved energy optimisation, albeit at a higher initial cost and level of complexity. The exact drying requirements, the resources at hand, and the desired balance between dependability and sustainability should all be considered while selecting a hybrid solar dryer.

Among all traditional solar dryers discussed above, indirect type solar dryers are frequently preferred to direct and mixed mode dryers for domestic users, farmers, and small-scale industries for various reasons as follows:

- Better Drying Control: Indirect sun dryers provide consumers with more control over the drying process by enabling them to adjust the humidity and temperature inside the drying chamber. For small-scale production and residential use, this control ensures more consistent and high-quality drying outcomes.
- Reduced Weather Dependency: Compared to direct solar dryers, indirect solar dryers are less dependent on exposure to direct sunshine. Since they can still function well on overcast or less sunny days, they are more dependable for users in areas with erratic weather patterns.
- Preservation of Product Quality: The indirect drying technique used in these dryers is typically softer than direct drying, which helps retain the dried products' inherent colours, flavours, and nutrients. This factor is particularly crucial for domestic consumers and small-scale businesses that place a high priority on product quality.
- Versatility: Food crops with higher moisture content can be dried using indirect solar dryers, which can handle a larger range of items. Due to their adaptability, users can dry a variety of crops, and other commodities without the need for separate dryers for each item.
- Reduced Risk of Contamination: For small-scale enterprises and household use, indirect solar dryers' closed drying chamber design helps shield the drying materials from external contaminants like dust, insects, or pollutants.
- Cost-effectiveness and simplicity: Indirect solar dryers, particularly passive ones, have a simpler design than mixed mode dryers. Since, they are more straightforward, residential consumers and small-scale companies can access and afford them more easily. This simplicity also lowers the initial investment and maintenance expenses.

- Environmentally Friendly: Indirect solar dryers, like other solar dryers, rely on the sun's renewable energy, making them sustainable and friendly to the environment. Many residential consumers and small-scale businesses looking for eco-friendly solutions can use these devices.
- Scalability: Indirect solar dryers are easily modified to work on a variety of scales, from small-scale residential use to large-scale farming or small-scale industrial uses.

While both direct and mixed mode solar dryers have advantages, indirect solar dryers are frequently preferred by residential users, farmers, and small-scale companies due to their improved control, dependability, product quality, and cost-effectiveness. The option is mainly determined by the users' individual demands, resources, and goals, as well as the scope of their drying operations.

1.2. Literature review

Post-harvest losses of agricultural products can be greatly reduced with utilisation of proper drying processes. Use of solar energy for drying is important. A critical technique for drying and conserving agricultural crops for future consumption is indirect type solar drying. Previous studies suggest that drying is a crucial, energyintensive process that constitutes difficult heat and mass transfer processes involving the crop and the drying medium. Previous research on indirect type solar drying points to the need for cost-effective, time-saving, and seasonally independent technologies for drying crops for preservation. The severe need for optimal and energy efficient drying processes led to study of various indirect type solar dryer designs, and ongoing research is being done in this area.

The advancements in indirect type solar dryers are discussed in this section. A brief discussion of recent improvements in indirect solar dryers, numerical computation of indirect solar drying systems including literature on exergy and energy analysis and several other associated factors such as drying rate, thermal efficiency, and economic analysis, several indirect type solar dryers' designs and performances are also discussed. This information aids in the adoption of such technologies in

accordance with the climatic conditions and the need to dry food crops. In recognition of the hard work put into crop production, the users receive a greater return and save time.

1.2.1. Advancement of Indirect type solar dryers

Gilago et al. [46] developed an indirect solar dryer shown in Figure 1.6. Performance of solar dryer with and without thermal storage for drying carrots under passive mode operation was evaluated and compared. This dryer setup dried the carrot samples from 9.13% moisture dry basis to 0.478 % moisture content dry basis. Dryer setup without thermal storage achieved desired moisture content in 16 hours while with thermal storage setup achieved it in 15 hours. Average drying efficiency of setup without thermal storage and with thermal storage was reported as 7.5% and 10.25% respectively.



Figure 1.6. Schematic showing passive indirect solar dryer with thermal energy storage [46]

Yassen et al. [47] designed and developed novel indirect solar dryer (NISD) and novel mixed indirect solar dryer (NMISD) as displayed in Figure 1.7. Further, both dryer's thermal performance was compared with the thermal performance of traditional indirect solar dryer (TISD). Novel indirect solar dryer consisted of flat plate solar collector, drying chamber, three drying wire mesh trays. The drying chamber walls were insulated using cork. A chimney was installed over the drying chamber which acted as air outlet.



Figure 1.7. Labelled picture showing three different experimental setups [47]

Etim et al. [48] designed and fabricated an active indirect solar dryer for drying banana. A total of 52 dryers were fabricated having 5 different levels and four shapes of inlet as shown in Figure 1.8. All these solar dryers were tested to find optimum design for drying banana. Data was obtained at an interval of 2 hours per day between the month of January and March. It was reported that moisture content in banana samples was reduced to 12 % wet basis from 68.97 % wet basis within 9 hours – 16 hours of drying in different dryers. It was concluded from the research that drying efficiency had been affected significantly by inlet area of solar dryer.



Figure 1.8. Aerial view of experimental setup [48]

Indirect forced convection solar dryer was developed by Vijayan et al. [49] for bitter gourd slices drying. Its setup consisted of a solar collector of 2 m² area, drying chamber and a blower placed at inlet of solar collector. Setup was tested for examining the effect of air flow rate on exergy and pickup efficiency of drying system. Bitter gourd was dried to 723 g from initial weight of 4000 g in 7 hours duration at 0.0636 kg/s air flow rate. Average exergy efficiency was in a range of 28.74% and 40.67% when mass flow rate of air varied between 0.0141 kg/s and 0.0872 kg/s. Furthermore, EPBT for an indirect solar dryer used for drying bitter gourd was reported as 2.21 years and CO₂ mitigation assessed for lifetime of the system was 33.52 years.

Sajith and Muraleedharan [50] investigated an integrated solar dryer system with a hybrid PV/T air heater. The hybrid PV/T system was made up of a double pass air heater and an indirect active solar dryer. The drying material for the system was amla (Phyllanthus emblica). The annualised cost technique was used to undertake the system's economic analysis. The system's payback period was determined to be 9.3 years, and the benefit-cost ratio was assessed to be 1.61. In addition, the energy payback time was predicted to be 2.25 years. With a carbon credit value of \$14.5 per tonne of CO2, the system was found to save Rs. 1003 per year on environmental costs.

Lingayat et al. [51] designed and developed an indirect type solar dryer. The dryer consisted of a solar flat plate collector with v-corrugated absorption plates, a drying chamber, four trays and a chimney as depicted in Figure 1.9. Dryer was tested in

unload condition and further used to dry banana. The drying efficiency and collector efficiency of solar dryer was reported as 22.38% and 31.5% respectively.



Figure 1.9. Schematic diagram of indirect type solar dryer [51]

Shrivastava and Kumar [52] developed an indirect solar drying unit. It had a drying chamber with two steel wire mesh trays, a solar air heater, and an air-supply device with four DC fans. The solar air heater heated the air that was fed to the drying chamber, which was used to dry fenugreek leaves. Using the DC fans, the air-supplying equipment forces ambient air into the solar air heater. The system's total embodied energy was 1081.83 kWh. The EPBT noted was 4.36 years, and the CO2 emissions observed were 391.52 kg per year. Nutrition values of dried fenugreek obtained from indirect solar dryer were examined and compared with open sun-dried fenugreek.

Sreekumar et al. [53] developed an indirect forced circulation solar dryer having two axial fans and a drying cabinet. Dryer was divided into top collector and a bottom drying chamber. Three experimental studies under no load and load conditions were performed. Maximum absorber temperature and maximum air temperature were achieved 97.2 °C and 78.1 °C, respectively. Crop dried in the dryer was bitter gourd which was dried in 6 hours in the system. Payback period of indirect type solar dryer for bitter gourd drying was estimated as 3.26 years. Pangavhane et al. [54] created a natural convection solar dryer that included a solar air heater and a drying chamber. This configuration was used to dry agricultural items such as fruits and vegetables. Grapes were employed as a crop in this study for drying in the newly built solar dryer. The qualitative research revealed that employing this approach reduces drying time significantly, as shade drying required 15 days and open sun drying took 7 days, the above set up took just 4 days to dry the grapes and the quality of the goods was also improved. As a result, the overall time required to dry the grapes was reduced by 43% when compared to open sun drying.

Amouzou et al. [44] in Togo, Africa, developed a brace type solar dryer, which had dimensions of $1.12m \times 1.3m \times 0.67m$ and a collector area of approximately $1m^2$. The absorber was built using a galvanized sheet and painted with black colour. Solar dryer was made from wood.

Table 1.1. gives brief overview of literature review on advancement of indirect type solar dryers.

Literature	System	Сгор	Parameters investi- gated	Reference
Gilago et al. (2023)	Indirect solar dryer	Carrot	Drying kinetics and thermal performance parameters	[46]
Yassen et al. (2021)	Novel indirect solar dryer (NISD) and novel mixed indi- rect solar dryer (NMISD)	-	Thermal performance was compared with the thermal perfor- mance of traditional indirect solar dryer (TISD) under unload conditions	[47]
Etim et al. (2020)	Active indirect so- lar dryer	Banana	Optimum design for drying	[48]

Table 1.1. Details of literature review on indirect type solar dryers

Vijayan et al. (2020)	Indirect forced con- vection solar dryer	Bitter gourd	Drying kinetics, ex- ergy and embodied energy	[49]
Sajith and Mura- leedharan (2020)	Integrated solar dryer system with a hybrid PV/T air heater.	Amla (Phyl- lanthus emblica)	Economic analysis and embodied energy	[50]
Lingayat et al. (2017)	Indirect type solar dryer	Banana	Thermal performance	[51]
Shrivastava and Kumar (2017)	Indirect solar dry- ing unit	Fenugreek leaves	Drying kinetics and embodied energy	[52]
Sreekumar et al. (2008)	Indirect forced cir- culation solar dryer	Bitter gourd	Thermal performance and embodied energy	[53]
Pangavhane et al. (2002)	natural convection indirect solar dryer	Grapes	Drying kinetics and quality analysis	[54]
Amouzou et al.brace type solar(1986)dryer			Performance analysis	[44]

1.2.2. Literature survey on numerical computation of solar dryers

Chavan et al. [55]developed a design of solar dryer to enhance flow rate of hot air. Two different designs of solar dryer were simulated using Ansys Fluent. CFD simulations were performed to fix location of exhaust fan and achieve optimum recycle ratio. Temperature contours, pressure contours and velocity contours were studied and compared to obtain best possible location for fan.

Singh et al. [56] utilized CFD modelling to assess the thermal and dynamic performance of an indirect forced convection solar dryer at various mass flow rates, using experiment results to validate the simulated data.

Mellalou et al. [57] built a modified greenhouse dryer with an uneven span and used CFD modeling to understand the temperature distribution within the dryer, validating the simulation with the findings from their experiments. Iranmanesh et al. [58] modelled, simulated, and fabricated a solar cabinet dryer equipped with evacuated tube solar collector. Dryer was simulated using Ansys Fluent software for predicting dryer's performance. Furthermore, experiments were performed at three different flow rates with and without phase change material to dry apple slices. Maximum overall drying efficiency was found 39.9% for dryer with phase change material.

Yadav and Chandramohan [59] designed and simulated two models of thermal energy storage for indirect solar dryer. A computational model was created to determine the influence of dryer fins on a thermal energy storage device. CFD simulations were performed for temperature and air flow velocities in designed thermal energy storage with fins and without fins. Both systems were compared based on results obtained from CFD simulations. Thermal energy storage with fins model was found best as per the simulation results.

Güler et al. [60] developed different designs of double pass indirect solar dryer with and without mesh absorber modification. CFD analysis was used to verify best possible design and based on numerical simulation results, double pass indirect solar dryer with mesh absorber modification (DPISDMA) was fabricated for experimentation. Maximum dryer efficiency for drying pepino fruit in DPISDMA was 23.08%. Drying kinetics of pepino fruit drying was performed and Logarithmic model was found suitable.

Demissie et al. [61] modelled and developed an indirect solar food dryer which contained a solar collector, drying chamber consisting of two columns of 4 rack shelves, chimney and solar powered fan. CFD simulation was applied to forecast temperature and air flow distribution inside the drying chamber. Steady temperature of 315 K was observed inside the drying chamber. Maximum temperature difference between experimental and simulation results was 4.3 K.

Jain et al. [62] analyzed a domestic direct multi-shelf solar dryer using ANSYS FLUENT software and evaluated the temperature distribution and pressure distribution of absorbed solar radiation. Simulation of the system was fully validated using experimental data under unload condition. Alonge and Obayopo [63] modelled and simulated a direct solar dryer for fish drying. Numerical simulations were performed to simulate different dimensions of modelled dryer at varying fan speed. Further, based on numerical simulation results, the dryer was fabricated and tested at unload condition. Maximum collector efficiency was reported as 77.2%.

Sanghi et al. [64] created a CFD model to simulate the performance of drying in a solar corn dryer, visualized temperature, humidity, and air velocity inside the dryer and validated the simulation results with experimental results. The anticipated temperature and humidity distributions were similar to the experimental measurements, while both temperature and humidity were overestimated by 8.5% and 21.4% respectively.

Dejchanchaiwong et al. [65] constructed and simulated mixed-mode and indirect solar dryers for natural rubber sheet drying. The study concluded that solar dryers drying time was reduced by 2-3 days along with improved dried product quality. The efficiency of the mixed-mode dryer was noted as 15.4%, which was greater than the efficiency of the indirect type solar dryer (13.3%).

Sonthawi et al. [66] designed a solar biomass hybrid dryer and modelled it using ANSYS-FLUENT CFD simulation software, analyzing the distributions of temperature and airflow. CFD simulations were performed under load conditions for rubber sheet drying to validate experimental results obtained. When statistical parameters were taken into account, the experimental temperature findings were substantially identical to the simulation results. During the 48-hour drying period, the moisture content of the rubber sheet decreased significantly from 34.2% to 0.34%.

Romero et al. [67] developed a prototype of indirect type solar dryer (TIKIN-2) for vanilla drying as displayed in Figure 1.10. Drying system was built using galvanised sheet metal to accumulate 50 kg vanilla for drying. It consisted of flat solar collector, cabinet, diffuser, chimney, and polycarbonate covering. Solar dryer's design was constructed using ANSYS design modeler and further validated using CFD simulation. CFD simulation results were compared with experimental results for validation. Solar dryer reduced 62% weight of vanilla after drying in one month which was three months during traditional drying method.



Figure 1.10. Indirect solar dryer prototype (TIKIN-2) [67]

Table 1.2. shows outcomes of literature survey on numerical computation of solar dryers.

Literature	System	Soft- ware used	Parameters investigated	Reference
Chavan et al. (2021)	Two different designs of solar dryer	Ansys Fluent	Temperature contours, pressure contours and ve- locity contours	[55]
Singh et al. (2021)	Singh et al. (2021) Indirect forced convec- tion solar dryer		Thermal and dynamic per- formance at various mass flow rates	[56]
Mellalou et al. (2021)	Modified greenhouse dryer	Ansys Fluent	Temperature distribution	[57]
Iranmanesh et al.Solar cabinet dryer(2020)ated tube solar collectortortor		Ansys Fluent	Three different flow rates with and without phase change material to dry ap- ple slices	[58]

Table 1.2. Literature survey on numerical computation of solar dryers

Yadav and Chan- dramohan (2020)	Two models of ther- mal energy storage for indirect solar dryer	Ansys Fluent	Temperature and air flow velocities with fins and without fins	[59]	
Güler et al. (2020)	Double pass indirect solar dryer	Ansys Fluent	Experimental validation	[60]	
Demissie et al.	Indirect solar food	Ansys	Temperature and air flow	[61]	
(2019)	dryer	Fluent	distribution	[01]	
Jain et al. (2018)	Domestic direct multi- shelf solar dryer	Ansys Fluent	Temperature distribution and pressure distribution	[62]	
Alonge and Obayopo (2018)	Direct solar dryer	Ansys Fluent	Experimental validation Selecting different dimen- sions for solar dryer at dif- ferent fan velocities	[63]	
Sanghi et al. (2018)	solar corn dryer	Ansys Fluent	Temperature, humidity, and air velocity	[64]	
Dejchanchaiwong et al. (2016)	mixed-mode and indi- rect solar dryers	Ansys Fluent	Validation of thermal per- formance	[65]	
Sonthawi et al. (2016)	Sonthawi et al. solar biomass hybrid (2016) dryer		Distributions of tempera- ture and airflow	[66]	
Romero et al. (2014)	Indirect type solar dryer (TIKIN-2)	Ansys Fluent	Experimental validation	[67]	

1.3. Research Gaps

Based on literature survey on various developed indirect solar dryers, following research gaps were identified:

- Compact and cost-effective dryer is required for domestic users.
- Dryer can be able to dry various crops efficiently without affecting the quality of dried products.
- Solar drying system integrated with sinusoidal corrugated type thermal collector has not been developed.

1.4. Research objectives

Based on research gaps, the following research objectives have been recognized:

- Design and development of domestic hybrid solar dryer
 - To study different solar drying systems and their recent developments.
 - Design a domestic hybrid solar dryer for north Indian climatic conditions.
 - Optimisation of designed system using Ansys- Fluent.
 - Fabrication of domestic hybrid solar dryer.
- Thermal performance evaluation of designed and developed solar dryer.
 - Under unload condition
 - \circ Under load condition
- Exergy analysis and drying kinetics of dried crop from designed and developed solar dryer.
- To discuss feasibility of the dryer for domestic users by computing various economic and environmental parameters.

1.5. Organisation of chapters

Based on the details of the work carried out in the present thesis, the thesis has been organized into six chapters.

Chapter 1: discusses crop drying, need for solar drying, classification of solar drying systems, mentions literature review, subsequently formulation of problem and research objectives.

Chapter 2: mentions design, development, fabrication, experimentation of under unload condition, evaluation of performance parameters, heat losses and CFD simulation of indirect domestic hybrid solar dryer.

Chapter 3: describes the experimentation of tomato drying in the dryer, assessment of drying kinetics of tomato drying in the system, evaluation of thermal performance, and finding suitable model for drying kinetics from various models.

Chapter 4: mentions the assessment of exergy, economic and environmental (3E) parameters and various sustainability indices of developed solar dryer and quality analysis of dried crop.

Chapter 5: mentions the design and development and CFD analysis of novel indirect type domestic hybrid solar dryer embedded with sinusoidal corrugated thermal collector.

Chapter 6: discusses the conclusions and future scopes of present work.

In the next chapter, design, method of fabrication, unload testing of indirect type domestic hybrid solar dryer has been discussed. Furthermore, thermal performance and heat loss assessment of the developed dryer has been evaluated and results from unload testing have been validated through the CFD simulation of designed solar dryer under unload condition.

CHAPTER-II

DESIGN, DEVELOPMENT, FABRICATION AND THER-MAL PERFORMANCE ANALYSIS OF INDIRECT TYPE DOMESTIC HYBRID SOLAR DRYER UNDER UNLOAD CONDITION

2.1. Introduction

Food drying is an important process of food processing techniques. Food drying is a high-energy-consuming method that needs enormous heat energy to eradicate moisture from the food crop [68], [69]. This heat energy is usually generated via electrical energy in industries which effect environment by producing $CO_2[3]$. This can be substantially saved by harnessing solar radiation [32], [69]. Open sun food drying is a prevalent technique for food drying at domestic levels [29], [62]. Although this process is free and widespread, it has more limitations, such as the deterioration of food by dust, rain, animals, and birds, emphasizing its less effectiveness [22], [29], [35], [62]. Therefore, it is better to opt for high efficiency and effective processes to save food deterioration at domestic and industrial levels. Solar food dryers harness solar energy for food drying efficiently and cleanly [70]–[72]. The food dried using these dryers has no chance of food deterioration due to dirt, pollution, and animals since the food is kept inside a closed chamber known as a dryer cabinet or drying chamber [53], [61], [73]. These dryers can be categorized into three types: direct, indirect, and mixed mode solar dryers as per their approach of harnessing solar energy for food drying [29], [32], [74]. Various researchers have also designed and simulated several kinds of solar dryers. CFD simulation is an efficient method of validating a designed product. It is a cost-effective tool that saves fabrication and trial of an unfeasible prototype time and money [62], [65], [66], [71].

Yadav and Chandramohan [19] designed an indirect solar dryer with finned copper tubes and established a mathematical model to determine the effect of fins on the dryer's thermal energy storing device. Demissie et al. [13] designed and performed CFD modelling on indirect solar food dryers using ANSYS FLUENT software. CFD simulation predicted the airflow distribution and temperature profile in the drying unit. Maximum average temperature variation between the observed and predicted theoretical temperatures was 4.3°C. Iranmanesh et al. [20] designed and fabricated a PCM-based solar dryer integrated with a heat pipe evacuated solar tube collector system. CFD modelling and thermal analysis of the system were completed for apple slice drying. Alonge et al. [21] modelled a direct solar dryer for fish drying purposes. Dryer was numerically designed, fabricated, and its performance was evaluated and compared with simulation results. Ashrabi et al. [22] designed a hybrid geothermal PCM solar dryer for industrial usage. Guler et al. [23] reported CFD analysis on an indirect solar dryer with low-cost iron mesh modifications. Singh et al. [23] constructed a multishelf solar dryer and tested it during stagnation condition. It was reported that maximum temperature attained and overall heat loss coefficient by the dryer was 100 °C and 8.5 W/m2K.

Abhay et al. [24] executed a numerical simulation on solar air collectors for the indirect type of solar dryer [ITSD]. Dejchanchaiwong et al. [25] implemented mathematical modelling on indirect and mixed-mode solar dryers for drying natural rubber sheets. Sonthawi et al. [18] reported a CFD simulation on a solar biomass hybrid dryer used for rubber sheet drying. Romero et al. [26] modelled an indirect solar dryer to dry 50 kg of vanilla by adapting ANSYS FLUENT to simulate results. Prakash and Kumar [27] presented the ANFIS design for the greenhouse dryer under passive mode to dry jaggery. Bartzanas et al. [28] used FLUENT v.5.3.18 software to investigate the tunnel greenhouse dryer design and vent arrangement's effect on air circulation. Mathioulakis et al. [29] simulated a batch-type tray dryer to dry fruits and used CFD FLUENT software to predict several factors to assess the system's performance.

Several researchers have performed simulations of different solar dryers by optimizing various design parameters [6,18,21–25,28–30]. Simulation of dryer and prediction of thermal behavior of the system are necessary for designing the solar dryer for crop drying.

Several solar dryers have been developed for industrial usage, but a few have been developed for domestic population. Moreover, previous literature lacks in evaluation of all heat loss parameters and thermal performances. In this chapter, a novel and compact indirect type domestic hybrid solar dryer has been proposed, fabricated and experimentally tested during stagnation condition to observe its performance. Prime advantage of the developed system is that firstly it does not utilise high grade energy and secondly it has high efficiency compared to open sun drying method, which is generally opted by domestic users for drying operations. The dryer contains an exhaust fan. It works on electricity generated by a PV module.

The developed dryer exploits solar thermal energy as well as electrical energy. So, it is termed as hybrid solar dryer system. Furthermore, heat losses through the collector were estimated. Overall heat loss coefficient, heat losses from side panels, bottom and top glazing has been assessed. Prime objective of this work is to propose a system with good thermal performance and less heat losses. Thermal performance parameters of ITDHSD's rectangular corrugated collector had been evaluated. The main benefit of proposed ITDHSD system was that it had higher heat utilization factor and collector thermal efficiency. During indirect mode, the dried crop quality will be better because the crop will be dried under shade. Further, validation of experimental results was done through CFD simulation results of ITDHSD in unload conditions.

2.2. Materials and Methods

2.2.1. System Description

An indirect type domestic hybrid solar dryer (ITDHSD) has been proposed, designed, fabricated, and installed on the rooftop of Delhi Technological University (DTU) campus, Delhi (India) (28.7496° N, 77.1174° E). The side view and rearview line diagrams have been displayed in Figure 2.1(a) and Figure 2.1 (b). ITDHSD system consists of frame developed from mild steel angles, drying cabinet, glass cover, solar collector, galvanised iron (GI) sheet absorber box, exhaust fan, photovoltaic module. Proposed components dimensions of the domestic hybrid solar drying system are reported in Table 2.1.





(b) rear view

Figure 2.1. Labelled line diagram of domestic hybrid indirect type solar dryer

Component	Materials used for fabrication	Dimensions
Solar collector	FRP (fiber-reinforced plastic) sheet, Toughened glass, Iron an- gles	1100×620×85 mm ³
Absorber box	Galvanized Iron (GI) sheet	1000×500×60 mm ³
Drying cabinet	FRP (fiber-reinforced plastic) sheet, Toughened glass, Iron an- gles	410×640×640 mm ³
Wire mesh trays	Stainless steel wire mesh, Alumi- num angles, Plywood, Aluminum handle	500×500 mm ²
Collector's inclination angle	_	28°
Outlet diameter	-	100mm

Table 2.1. Components of the domestic hybrid type solar dryer and their dimensions

2.2.2. Fabrication

The dryer was fabricated at Centre for Energy and Environment, Delhi Technological University, Delhi (India)campus. The base frame of dryer system was constructed from mild steel angles welded together. Figure 2.2 shows the fabricated base frame of the dryer. System was mounted on the base frame. It is portable and can be moved with the help of castor wheels.



Figure 2.2. Base frame of domestic indirect type solar dryer

Figure 2.3 shows the fabrication of solar collector. The solar absorber was gas welded in the form of a hollow box. The rectangular corrugated solar collector consists of a metal absorber box made from galvanized iron sheet (thickness 5 mm). Seven arrays consisting of four rectangular corrugated fins (length 50 mm and width 10 mm) in each array were attached to the top face of absorber box. Carbon coating has been done by painting the outer layer of galvanized iron sheet (GI sheet) absorber box to ensure maximum solar flux absorption inside the absorber box. Rectangular corrugation was provided to enhance heat transfer rate to air from the absorber.



Figure 2.3. Fabrication of absorber box for indirect type domestic hybrid solar dryer

Figure 2.4 shows the unfinished indirect solar dryer. The drying cabinet and collector's base were fabricated using 3 mm thick fibre reinforced plastic (FRP) sheets. Drying cabinet consisted of three rectangular sliding wire mesh trays and an exhaust fan installed with a photovoltaic (PV) module at the upper part of the drying cabinet. Sliding food trays were made of stainless-steel wire mesh, which is nontoxic and prevents corrosion. Aluminum handles were attached to move food trays in the drying cabinet.



Figure 2.4. Basic structure of indirect solar dryer

Figure 2.5 and Figure 2.6 displayed the indirect solar dryer components and its front and back view. Glass cover (thickness 5 mm) was placed at the top of the drying cabinet and solar collector. Therefore, the proposed and fabricated dryer can work as both indirect and mixed-mode dryers depending on the dried crop. Top glass cover over the drying cabinet should be covered using suitable insulation during indirect mode operation. Box built from timber plywood was placed at the bottom of the drying cabinet to keep the measuring instruments. Electrical energy generated by the PV module has been utilized to run the exhaust fan mounted at the outlet of the drying cabinet. This makes ITDHSD self-sustainable drying system.



Figure 2.5. Fabricated domestic hybrid solar dryer



Figure 2.6. Backside of indirect type domestic hybrid solar dryer

In the above system, the crop to be dried will be placed over the sliding trays in the drying cabinet. Metal absorber box placed inside the collector absorbs direct sunlight that falls over the solar collector. A polished stainless steel sheet has been placed at south facing wall of the solar dryer. This reflects solar radiation falling towards the solar collector which helps in enhancing the absorption of solar radiation by solar collector. Air from the solar collector inlet flows over the tray, and the air temperature rises through convection heat transfer mode. Further air movement inside the drying cabinet transfers its heat content to the crop. Henceforth, moisture was removed with the help of air through a vent presented at the topmost section of the drying cabinet. A fan over the outlet vent helps maintain continuous airflow from domestic hybrid solar dryer setup [5,30]. Air circulation took place during active mode due to the fan installed inside the drying cabinet. Photograph of domestic hybrid solar dryer system is shown in Figure 2.7.



Figure 2.7. Labelled snapshot of indirect type domestic hybrid solar dryer during stagnation experimentation

Further, the fan can function sustainably during sunshine hours without utilizing conventional energy sources. Excess air inside drying cabinet is continuously removed by fan to achieve better crop drying.

2.2.3. Experimental Observations and Instrumentation

Experiments were performed during November 2021 (winter season) at Delhi Technological University (DTU), Delhi (India). During experimentation, clear sky condition was observed. For stagnation state testing, inlet and outlet ports of drying system were covered to avoid airflow inside the system. The following parameters were measured during the experiment: ambient temperature (T_a), inlet velocity (V_i), ambient relative humidity (R_{ha}), global solar insolation (I_g), diffused solar insolation (I_d), temperature at different places of solar dryer.

During the experimentation, temperature at various places inside the indirect domestic hybrid solar dryer was recorded using twelve K-type (Make- Tempsens T-101, material- Chromium- Aluminum (Cr-Al), Range- 0-400°C) thermocouples as shown in Figure 2.8. The photovoltaic module (20 W, 12 V) was opaque with a fill factor value of 0.8. The thermocouples tips were shaded from the top using paper tapes to avoid the error, which can be generated in readings due to direct solar radiation falling on the tip of thermocouples. A 12 channel datalogger (Make- Sunpro Instruments (India), Range- -50°C to +1210°C) was used to get the thermocouples' temperature values. Global and diffused solar radiation were measured using solar power meter (Make-General tools, Model- DBTU1300, Range-0 to 2000 W/m²). A thermohygrometer (Make- Testo 625; range- 0 to 100% RH) was used to compute the relative humidity of air in system. A thermal anemometer (Make- Testo 405, range: 0 to 10 m/s) was used to measure the air velocity. Observation table for stagnation experimentation is displayed in Table 2.2.

2021									
Time (hours:min)	Ig (W/m ²)	I _d (W/m ²)	R _{ha} (%)	Va (m/s)	T _{ab} (K)	Tg (K)	Ta (K)		
09:00	475	97	54.1	0.4	315.15	311.15	296.15		
10:00	535	109	51.6	0.5	332.15	316.15	297.25		
11:00	591	126	46.1	0.35	345.15	322.15	298.45		
12:00	623	160	45.3	1.2	358.15	327.15	300.15		
13:00	702	155	46	1.51	371.15	336.15	302.25		
14:00	645	126	42.6	0.9	364.15	335.15	301.15		
15:00	578	109	42.3	1.1	357.15	331.15	298.55		
16:00	465	96	44.5	0.62	343.15	320.15	296.25		

Table 2.2. Observations noted during stagnation experimentation of solar dryer on 15th November

Where I_g is global solar radiation , I_d is diffused solar radiation , R_{ha} is relative humidity, T_a is ambient temperature, V_a is ambient air velocity at dryer's top surface, T_{ab} is absorber temperature, T_g is temperature of collectors' top glass

		Ambient Parameters					Tempe	rature m	easured a	at differe	ent poir	nts of I	ndirect ty	ype do	mestic hy	brid sola	ar dryer ((in K)
S.No.	Time	Ig (W/m ²)	I _d (W/m ²)	R ha (%)	Ta (K)	Vi (m/s)	T ₁	T ₂	T ₃	T4	T 5	T ₆	T 7	T ₈	T9	T ₁₀	T ₁₁	T ₁₂
1	09:00	432	70	52.7	294	0.1	296.2	297.2	305.2	309.2	311	312	309.2	302	301.2	301.2	302.2	303
2	10:00	510	97	50.3	296	0.17	299.2	308.2	310.2	315.2	318	315	313.2	304	303.2	303.2	304.2	305
3	11:00	535	110	48.2	297	0.16	302.2	310.2	313.2	318.2	320	317	315.2	305	304.2	304.2	305.2	305
4	12:00	565	115	46.4	297	0.29	304.2	312.2	315.2	321.2	321	318	317.2	306	304.2	304.2	306.2	307
5	13:00	644	123	41.9	299	0.31	305.2	317.2	323.2	328.2	326	321	321.2	308	307.2	306.2	307.2	308
6	14:00	660	112	39.7	299	0.37	307.2	318.2	326.2	327.2	323	320	319.2	306	305.2	304.2	306.2	307
7	15:00	585	105	44.2	298	0.4	304.2	314.2	320.2	322.2	318	319	315.2	303	302.2	302.2	304.2	306
8	16:00	424	80	50.2	298	0.3	301.2	301.2	312.2	317.2	312	311	309.2	301	300.2	300.2	301.2	303

Table 2.3. Mean observations noted during unload experimentation of indirect domestic hybrid solar dryer

Where I_g is global solar radiation in W/m², I_d is diffused solar radiation in W/m², R_{ha} is relative humidity in %, T_a is ambient temperature in K, V_a is ambient air velocity at dryer's top surface in m/s, V_i is inlet air velocity in m/s, T_1 is Inlet air temperature, T_2 is Air temperature above collector surface, T_3 is Upper glass temperature, T_4 is Collector surface temperature 1, T_5 is Collector surface temperature 2, T_6 is Collector surface Temperature 3, T_7 is Collector outlet temperature, T_8 is temperature above tray1, T_9 is temperature above tray2, T_{10} is temperature above tray3, T_{11} is air temperature at the exhaust, T_{12} is temperature above the upper glass of dryer cabinet.



Figure 2.8. Labelled line diagram of ITDHSD showing positions of thermocouples

2.2.4. Methodology

Hourly observations were noted from 09:00 to 16:00 hours during the day. Observations have been taken for ambient temperature, inlet air velocity, global and diffused solar insolation, relative humidity, and temperature inside the domestic hybrid indirect type solar dryer. Twelve K-type thermocouples were placed inside the solar dryer to measure the temperature. Three thermocouples were attached to the solar collector's absorber box and three inside the drying cabinet. Average temperature values were taken to calculate the temperature value at the solar collector and drying cabinet and have been shown in Table 2.3. After noting the parameters, coefficient of performance (COP), heat utilization factor (HUF), heat gain by air, thermal efficiency were computed from Eqs. 2.3, 2.4, 2.5, and 2.6, respectively. While experimenting, the solar collector was inclined at an angle of 28° (latitude Delhi, India).

2.2.4.1. Validation

Data generated from numerical simulation of ITDHSD was validated using experimental data. Linear regression analysis based on R^2 (coefficient of determination) and adjusted R^2 method was performed to validate the data [75], [76].

$$R^{2} = 1 - \frac{\sum_{i=1}^{n} (T_{pre,i} - T_{exp,i})^{2}}{\sum_{i=1}^{n} (T_{exp,i})^{2}}$$
(2.1)

$$(\bar{R})^2 = 1 - (1 - R^2) \frac{n_1 - 1}{n_1 - p_1 - 1}$$
(2.2)

where n_1 and p_1 are the no. of repressors in the model and the sample size, T_{pre} signifies the predicted values, and T_{exp} is the experimental values.

2.2.4.2. Experimental uncertainty

Uncertainty in the experimental readings was unavoidable for several reasons viz. selection of inappropriate devices, surrounding conditions, accuracy and readability of selected instruments and other human inaccuracies [49]. In drying experiment, it was necessary to evaluate the highly probable uncertainties in the independent parameters such as velocity, solar insolation, weight, temperature, and critical calculated design parameters such as mass flow rate of air, efficiency, drying rate, and heat gain. The uncertainty values of several parameters are mentioned in Table 2.4. The estimated result E is the given function for independent variables. Consider x_E is the uncertainty in the estimated results and x_1, x_2, \ldots, x_n be the independent variable uncertainties. E is the function of the independent variables v_1, v_2, \ldots, v_n . Then, the uncertainty in the result can be estimated as:

$$x_E = \sqrt{\left(\frac{\partial E}{\partial v_1} x_1\right)^2 + \left(\frac{\partial E}{\partial v_2} x_2\right)^2 + \dots + \left(\frac{\partial E}{\partial v_n} x_n\right)^2}$$
(2.3)

S.No.	Independent variables	Uncertainty
1.	Air velocity measurement (x _{AVM})	±0.1 m/s
2.	Temperature measurement (x _{TM})	±0.1 °C
3.	Weight measurement (x _{WM})	±0.001 kg
4.	Solar insolation measurement (x _{IM})	$\pm 10 \text{ W/m}^2$
5.	Relative humidity measurement (x _{RHM})	±3%

Table 2.4. Uncertainty values of various measured variables during experimentations in ITDHSD

2.2.5. Heat losses through collector

Solar collector is an essential component which absorbs solar energy falling over it and transfer it to air flowing inside it. To utilise maximum absorbed energy, it is important to calculate all heat losses. Various heat losses from collector are discussed as follows:

2.2.5.1. Overall heat transfer coefficient (Uo)

The equation for calculation of overall heat transfer coefficient through solar collector can be written as [77]:

$$I_{g}(\tau \alpha_{s}) = U_{O}(T_{ab} - T_{a})$$
(2.4)

2.2.5.2. Total heat loss (qL)

Total heat loss from the solar collector is the sum of losses from the side panels, bottom, and through top glazing of solar collector and it can be written as [78]:

$$q_L = q_{sp} + q_b + q_g (2.5)$$

2.2.5.3. Heat loss from side panels (qsp)

Side panels of ITDHSD were made from fibre-reinforced plastic. Heat loss from side panels can be given as [77], [78]:

$$q_{sp} = \left(\frac{A_{sp}(T_{ab} - T_a)}{\frac{X}{K}} + \frac{1}{h}\right)$$
(2.6)

2.2.5.4. Heat loss from bottom (q_b)

Bottom of ITDHSD was insulated using 10 mm glass wool insulation. The thermal conductivity of glass wool is taken as 0.136 W/m K. Bottom heat loss is estimated using [78] :

$$q_b = \frac{A_b(T_{ab} - T_a)}{(\frac{X}{K})}$$
(2.7)

2.2.5.5. Heat loss from top glazing (qg)

Heat loss from top glazing includes heat loss by convection from air flowing over the glazing and heat loss from radiation. The equation of heat loss from glazing can be expressed as [78], [79]:

$$q_g = (h_g + \varepsilon h_r) A_g (T_g - T_a)$$
(2.8)

2.2.6. Thermal Performance Parameters

The unload experiment data investigated the thermal performance parameters to evaluate the ITDHSD design and performance under active mode. This evaluation is necessary to determine a solar dryer's ability to utilize and convert the radiant solar insolation to thermal energy. Following thermal performance parameters were calculated for ITDHSD during active mode operation:

2.2.6.1. Coefficient of performance (COP)

It is the fraction of the difference in temperature between drying cabinet inlet temperature (T_{dc}) and ambient temperature (T_a) to the difference in temperature between solar collector's absorber plate (T_{sc}) and ambient. The expression to calculate COP [62], [80] is as follows:

$$COP = \frac{(T_{dc} - T_a)}{(T_{sc} - T_a)}$$
(2.9)

2.2.6.2. Heat utilization factor (HUF)

It is related to the decrease in temperature due to air cooling and increased temperature due to air heating [43], [62]. The expression to evaluate HUF is as follows:

$$HUF = \frac{(T_{sc} - T_{dc})}{T_{sc} - T_a}$$
(2.10)

2.2.6.3. Heat gain by air (Q_a)

The heat is absorbed by the air flowing through the collector. The heat absorbed can be calculated by measuring air temperature at the inlet and exit of the collector [81]. The expression for heat gain by air is as follows:

$$Q_a = \dot{m}c_{pa}(T_e - T_i) \tag{2.11}$$

2.2.6.4. Thermal efficiency $(\eta_{thermal})$

Thermal efficiency is defined as the ratio of thermal energy absorbed by air from solar collector to the solar energy input to the collector. It is expressed as [82]:

$$\eta_{thermal} = \frac{Q_a}{I_g A_{sc}} \tag{2.12}$$

2.2.7. Simulation Approach

Simulation of designed and developed systems through simulation software such as ANSYS, COMSOL, MATLAB etc. is essential to validate the system design and performance [71]. Several researchers used different software and validated their system. Here, ANSYS-FLUENT software had been used to simulate the system performance and validate system's design. The governing equations, assumptions and boundary conditions used for simulation of system are as follows:

2.2.7.1. Governing Equations

To simulate the designs of ITDHSD system, proper equations were selected and resolved using ANSYS-FLUENT. Expressions for solving several conservation equations [62], [66] to estimate the system performance are as follows:

Mass conservation equation:

$$\frac{\partial \rho_s}{\partial t} + \nabla (\rho_s \boldsymbol{v}) = 0 \tag{2.13}$$

Momentum conservation equation:

$$\frac{\partial}{\partial t}(\rho_s \boldsymbol{v}) + \nabla . (\rho_s \boldsymbol{v} \boldsymbol{v}) = -\nabla \mathbf{p} + \rho_s \mathbf{g} + \mathbf{F}$$
(2.14)
Energy conservation equation:

$$\frac{\partial}{\partial t}(\rho_s E) + \nabla [\nu(\rho_s E + p)] = 0$$
(2.15)

Heat transfer radiation:

$$\frac{dI(r,s_n)}{ds_n} + (a_s + \sigma_s)I(r,s_n) = a_s n^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{\pi} \int_0^{4\pi} I(r,s_n)\phi(s_n,s')d\Omega'(2.16)$$

To resolve Eq. 2.16, ANSYS-FLUENT contains a solar load model to determine the consequences of sun's radiation that arrive in a computational realm. Moreover, it included a solar calculator to locate the sun's position in the sky at the specified phase.

2.2.7.2. Boundary conditions

Following boundary conditions were considered for numerical simulation of ITDHSD:

- Ambient temperature was considered the initial temperature of the system. The problem was taken as three-dimensional and steady-state.
- Airflow rate was taken as 1.2 kg/sec in case of forced convection mode drying.
- Dryer wall was considered motionless and equipped with insulation.
- All surfaces in the design were considered smooth, and fluid flow was frictionless.
- All parts of the system were taken for the meshing procedure to obtain good results from the CFD analysis.
- Solar load model was considered for determining the effects of suns' radiation entering a computational realm. k-ε model was considered to get an accurate picture of heat transfer and air circulation in solar dryers.
- Number of iterations for the simulation was set at about 3000. Temperature contour and solar heat flux contours were plotted using ANSYS-FLUENT.

2.3. Results and Discussion

2.3.1. Experimental results

Experiments under stagnation conditions were performed on 15 November 2021, during winter months at Delhi Technological University (DTU), Delhi. Hourly observations were taken for ambient parameters viz. ambient temperature, air velocity, relative humidity, and global and diffused solar insolation. Observations for stagnation experimentation is displayed in Table 2.2. Figure 2.9 displays the hourly recorded ambient parameters. It can be observed that solar insolation and ambient temperature were in the range of 465-702 W/m² and 296-302.1 K, respectively during experimentation. Climate was sunny and clear sky throughout experimentation.



Figure 2.9. Ambient parameters during stagnation experimentation

Inlet and outlet ports were closed during stagnation experimentation. This leads to an increase in temperature at solar collector due to absence of airflow inside collector. Figure 2.10 shows variation of temperature at absorber, top of collector glazing, and ambient temperature. Absorber temperature reached 371 K at 13:00 hours when the ambient temperature was 302.1 K and global solar insolation was 702 W/m^2 . This depicts that collector can absorb a good amount of thermal energy from solar radiation.



Figure 2.10. Temperature variation at absorber, top of collector glazing and ambient during stagnation experimentation

Table 2.2 shows various losses that occur in the solar collector during experimentation. The average value of overall heat loss coefficient U_0 during experimentation was estimated from Eq. (2.4) as 10.25 W/m² K which was much less for the solar collector. Other values of losses such as heat losses from side panels, bottom, top of glazing was estimated using equations (2.6) - (2.8).

Total heat loss as calculated from Eq. (2.5) was in the range of 262.63- 619.80 W. This included all other losses i.e. heat losses from side panels, bottom, top of glazing. Sides were made from fiber-reinforced plastic material (FRP sheets) which is a good insulator. Also, contact area of side panel was 0.0935 m² which was very less. Hence, side panels had less heat loss. Bottom side was insulated using 10 mm thick glasswool insulation. Maximum heat loss occured at top glazing which had

no insulation over it. Table 2.5 shows hourly values of overall heat transfer, side losses, bottom losses, top losses and overall losses.

	Overall heat	Heat loss	Heat loss	Heat loss	Overall
Time	loss coeffi-	from side	from bot-	from glass top	heat loss
Time	cient (U ₀₎	panels (q _{sp)}	tom q _b	(q _g)	(q L)
	W/m ² K	(W)	(W)	(W)	(W)
09:00	19.73	11.84	107.02	143.76	262.63
10:00	12.04	15.19	138.10	185.50	338.80
11:00	9.99	18.88	171.95	230.95	421.79
12:00	8.45	21.62	198.21	266.19	486.03
13:00	7.94	27.51	252.82	339.47	619.80
14:00	8.01	27.25	250.05	335.76	613.07
15:00	7.82	25.44	233.45	313.50	572.40
16:00	8.03	18.09	165.04	221.67	404.81

 Table 2.5. Estimated values of overall heat loss coefficient and other losses for solar collector during stagnation state

Under unload condition in active mode domestic hybrid solar dryer, the experiments were conducted three times from 16th -18th November 2021. Average of hourly observations (Table 2.3) were taken into consideration for evaluating thermal performance parameters. Observation tables for unload experimentation were displayed in Table 2.2 and Appendix I, II and III. Global and diffused solar insolation under unload condition testing during active mode, are reported in Figure 2.11. The trend showed that the global solar insolation and temperature enhanced from 09:00 to 13:00 hours. After 13:00 hours, the temperature reduced, and after 14:00 hour, global solar insolation also decreased gradually with time. The range of global and diffused solar insolation was observed as 424-660 and 70-123 W/m^2 respectively. Ambient relative humidity was reduced as the day progressed, and at 14:00 hours, it was at lower levels of the day. As solar insolation reduced, a rise in relative humidity was observed.



Figure 2.11. Hourly trends of Ambient parameters namely, ambient relative humidity (R_{ha}), global solar insolation (I_g), diffused solar insolation (I_d)) under unload condition experiment during active mode

Ambient temperature range was 294.25 – 303 K. Temperature inside ITDHSD increases as the ambient temperature increases. Solar insolation absorbed by the solar collector assisted in increasing the air temperature. Trends in Figure 2.12 showed that the maximum ambient temperature was highest at 13:00 hours during the day, and corresponding solar collector and drying cabinet temperature were also maximum. Maximum average solar collector and drying cabinet temperature were observed at 325.15 K and 307.15 K.



Figure 2.12. Hourly trends of observed temperature (Average solar collector temperature (T_{sc}) , Average drying cabinet temperature (T_{dc}) , and Ambient temperature (T_a)) in the domestic indirect solar drying system experiment

The variation in COP and HUF for ITDHSD has been given in Figure 2.13. The range of COP and HUF of ITDHSD was found to be 0.18-0.44 and 0.56-0.81 respectively as evaluated using Eqs. (2.9) - (2.10). COP of the solar dryer has been maximum during the morning time, and HUF is maximum during the evening. HUF increases as the time of the day increases, and COP of the dryer decreases. Due to the rise in solar insolation, the solar collector has absorbed more thermal energy.



Figure 2.13.: Variation in heat utilisation factor and coefficient of performance of ITDHSD with respect to time

It can be observed that the thermal efficiency (Figure 2.14) of the solar collector is maximum during 13:00 hours. This was due to high solar irradiance falling on the solar collector. At 14:00 hours, the solar irradiance was highest, but due to lesser temperature and higher mass flow rate (0.26 kg/s), it resulted in higher convection losses. The range of collector's thermal efficiency was found to be 31-59% as evaluated using Eq. (2.12).



Figure 2.14. Hourly variation of measured mass flow rate of working fluid (air) and thermal efficiency of ITDHSD's collector

2.3.2. Simulation Results

CFD analysis evaluated the temperature and airflow distribution pattern inside the ITDHSD. Various input design parameters applied during simulation have been given in Table 2.6.

Parameter	Value					
Ambient Temperature, T	300 K					
Airflow rate, \dot{m}_a	1.2 kg/s during active mode					
Heated wall	glass sheet					
Thickness of heated wall, t	8 mm					
Other walls	Insulated					
Specific heat capacity of air, C _{pa}	1.007 kJ/kg K					
Density of air, ρ_s	1.164 kg/m ³					
Viscosity of air, μ_a	$1.872 \times 10^{-5} \text{kg/ms}$					
Thermal conductivity of air, Ka	0.02588 W/m-K					
Specific heat capacity of glass, C_{pg}	0.75 kJ/kg K					
Thermal conductivity of glass, K _g	1.05 W/m-K					
Density of glass, ρ_g	2500 kg/m ³					
Absorptivity of glass, α_s	0.1					
Transmissivity of glass, $ au$	0.8					
	According to solar ray tracing module of					
Solar Insolation	ANSYS FLUENT					
Date	21 st November					

Table 2.6. Various input parameters applied during simulation

Figure 2.15 illustrates the design of the ITDHSD comprising a solar collector and drying cabinet unit. Air flows inside the solar collector and moves upwards to the drying cabinet's top section towards the drying cabinet's outlet.



Figure 2.15. Design of domestic hybrid indirect solar dryer in ANSYS FLUENT

Grid independence test was performed over dryer mesh as given in Table 2.7. Grid density of 3,05,000 was generated for indirect solar dryer. Generated grid was of tetrahedral shape. Solar load scheming of ANSYS FLUENT was considered for the simulation of ITDHSD.

S. No.	Mesh Type	No. of nodes	No. of ele- ments	Temperature (K)
1.	Tetrahedral/mixed	1,50,000	1,66,000	340
2.	Tetrahedral/mixed	2,00,000	2,06,000	328
3.	Tetrahedral/mixed	2,50,000	2,52,000	324
4.	Tetrahedral/mixed	3,00,000	3,05,000	322
5.	Tetrahedral/mixed	3,20,000	3,23,000	322

Table 2.7.	Grid	Inde	pendence	test
1 4010 2000	0110	111000	penaenee	

Absorbed solar flux inside the indirect type domestic hybrid solar dryer during active mode has been illustrated in Figure 2.16. It can be observed that solar collector absorbed maximum solar radiation. *This validated ITDHSD's design following Ajunwa et al.* [83]. Solar heat flux contours indicated that solar collector has absorbed incident solar insolation, further maintaining drying air temperature. Working fluid (air) at an initial temperature of 300 K approaches the solar collector system's inlet, and air gets heated, and its temperature will rise as it approaches dryer's outlet. It happens due to thermal energy absorbed by solar collector from solar radiation. Solar heat flux generated at solar collector can be noted as 430.76 W/m². Outer side of the solar drying unit is insulated. Therefore, a relatively small solar heat flux can be observed at outer wall of drying cabinet.



Figure 2.16. Absorbed solar flux (W/m²) inside domestic indirect type solar dryer

Static contour showing temperature variation inside a domestic indirect type of solar dryer during active mode at 12:00 PM has been illustrated in Figure 2.17. The collector temperature was 350 K, and it was observed that air temperature rises at an optimum value of 325 K at the solar collector outlet due to controlled airflow. Air at ambient temperature absorbs heat from solar collector due to various heat transfer modes, namely conduction, convection, and radiation. This air circulates upwards towards the outlet of the solar dryer system due to fan installed at the dryer's outlet. Therefore, temperature decreases to 322 K inside dryer cabinet. Heat losses were minimal due to insulation provided at the dryer's outer surface. The temperature inside the drying cabinet is optimum for crop drying and saves texture and taste of dried crops.



Figure 2.17. Temperature variation (K) inside ITDHSD during the active mode

2.3.3. Validation results

Figure 2.18 shows the curves of experimental and predicted collector temperature of ITDHSD system. R^2 and adjusted R^2 for the experimental and predicted data were evaluated using Eqs. (2.1) - (2.2) as 0.9774 and 0.9738, respectively. Therefore, predicted, and experimental values were found to be in fair agreement.

Furthermore, absorbed solar flux inside the indirect type domestic hybrid solar dryer during active mode was maximum at solar collector as observed from Figure 2.16. Ajunwa et al. [83] stated that solar collectors should absorb maximum solar radiation. This statement validated simulated design of ITDHSD system.



Figure 2.18. Hourly variation of theoretical and experimental collector temperature of ITDHSD

2.4. Comparison with existing solar dryers

The performance of ITDHSD has been compared with other solar dryers as displayed in Figure 2.19. The maximum thermal efficiency of ITDHSD was found highest among the other solar dryers. ITDHSD had maximum collector efficiency of 59% while system developed by Sootodeh et al. [84], Simate and Cherotich [85], Singh et al. [86], Blaise et al. [87], Lingayat et al. [51], had maximum collector efficiency of 26.3%, 24.7%, 43%, 43.4%, and 31.5% respectively.



Figure 2.19. Comparison of ITDHSD's maximum collector efficiency with other solar dryers

2.5. Summary

ITDHSD system was designed, simulated, and fabricated at the rooftop of Delhi Technological University (DTU), Delhi (India). The experiment under stagnation and active mode for unload condition was successfully concluded from $15^{\text{th}} - 18^{\text{th}}$ November 2021, respectively. Further, heat losses and thermal performance parameters of ITDHSD system were evaluated. From the above discussion, the following conclusions were drawn:

- Under stagnation state, maximum temperature reached during winter month of November was 98°C while the ambient temperature was 29.1 °C.
- Average overall heat transfer coefficient for the solar collector was 10.25 W/m²
 K.
- Losses were maximum from the glazing side and minimum at side panels.
- HUF increases as the time of day increases, and COP of ITDHSD decreases.
- Thermal efficiency of the solar collector in the ITDHSD had a maximum value of 59% at 13:00 hours.

- In ITDHSD, the major area of the solar collector captured adequate radiation flux as per simulated data.
- The experimental and simulated results were in fair agreement as evaluated using linear regression analysis.
- The designed ITDHSD collector had highest thermal efficiency as compared to other solar dryer systems.

In next chapter, tomato drying experimentation in indirect domestic hybrid solar dryer has been discussed and drying kinetics, thermal performance and statistical analysis for tomato drying have been assessed in detail.

CHAPTER-III

DRYING KINETICS AND THERMAL PERFORMANCE ASSESSMENT OF SOLANUM LYCOPERSICUM (TO-MATO) IN INDIRECT TYPE DOMESTIC HYBRID SO-LAR DRYER (ITDHSD) SYSTEM

3.1. Introduction

Deterioration of consumable foodstuff is a foremost challenge to the world. Emerging nations are severely facing the crisis as a substantial part of consumable foodstuff is lost due to mutilation by pests, and careless handling [32], [62]. Postharvest drying is a crucial activity of food processing [88]. Excess moisture is removed from food grain using drying process, which helps preserve the food grains [22]. Usual drying practices are air drying, open sun drying, and drying through conventional electrical dryers [29]. Conventional electrical dryers are expensive, and not environmentally friendly. Traditional technique that has been accepted for food drying at domestic level is open sun drying under direct sunlight [69], [89]. There have been many shortcomings and disadvantages of this drying method. Open sun drying is dependent on weather and has other disadvantages like deterioration of food due to the development of microorganisms, birds, animals, insects, etc. Solar dryers help to solve these problems and are more efficient, uniform, and economical [29], [88], [90]. Solar dryers have many advantages over traditional methods like reducing the use of fossil fuels, reduction in emission of greenhouse gases, reducing machinery use, and reduction in losses of food grains post-harvest [1], [66]. Food grains dried by such a method can be stored longer [91], [92]. Solar dryers can be categorized into three main categories: direct, indirect, and mixed mode [29], [32].

Lingayat et al. [93] fabricated an indirect type solar dryer and studied its performance and drying kinetics of tomato and brinjal slices. Abuelnuor et al. [94] fabricated a solar dryer and dried tomato under indirect mode. It was reported that tomato slices were dried in 10 hours. Ramirez et al. [95] analysed an indirect solar dryer with and without PCM. Vijayan et al. [49] developed an indirect forced convection solar dryer for bitter gourd slices drying. Noori et al. [96] developed an active indirect solar drying system that consisted of a rectangular drying cabinet and a flat plate thermal collector. Tomato slices were dried at an ambient temperature of 17.6°C, and the final moisture content of 22% was achieved in 30 hours. Abideen et al. [97] fabricated an indirect solar dryer for tomato drying. Noutfia et al. [88] developed and dried figs in an indirect solar dryer utilized for small farms.

Shrivastava et al. [98] examined drying kinetics of fenugreek in an indirect solar dryer without varying mass flow rates. Srivastava and Shukla [99] validated theoretical thermal modelling of an indirect solar dryer through experiment with potato crop drying. Dejchanchaiwong et al. [65] developed and tested an indirect solar dryer for natural rubber drying. Gupta et al. [100] constructed and evaluated performance of indirect solar dryer with tomato crop drying. Overall drying efficiency was found to be 17%. Hosaain et al. [101] developed a hybrid solar dryer for drying tomato. Maximum dryer efficiency during daytime was reported as 29.35%. Sreekumar et al. [53] developed a forced convection indirect solar dryer and dried bitter gourd.

All available literature on tomato drying in a compact sized dryer lacked in evaluation of exergy analysis of solar PV module used to run a fan. Moreover, an essential factor of equivalent moisture content was neglected in the literature during calculation of moisture ratio, which cannot be neglected in drying high moisture crops in tropical areas with high relative humidity. Tomato (Solanum lycopersicum) crop has been taken, dried and experimented, since it has high moisture content. In this chapter, the aims of the experiment conducted are:

- to estimate initial moisture content of Solanum lycopersicum (tomato) crop,
- (ii) to evaluate the transient moisture content of Solanum lycopersicum
 (tomato) crop at different trays in the drying cabinet of domestic hybrid solar dryer under indirect mode operation,
- (iii) to investigate different performance parameters of ITDHSD,
- (iv) to analyse an appropriate drying model for Solanum lycopersicum (tomato) crop.

3.2. Materials and Methods

3.2.1. Experimental Procedure and Observations

Four-kilogram tomato from local market were purchased, washed, and dried properly before slicing. Further, slices of thickness 3-5 mm were evenly placed in three different trays during experimentation, i.e., one kilogram in each tray1, tray2, and tray3, for drying. One kilogram of tomato was used for open sun drying. Initial moisture content of Solanum lycopersicum (tomato) slices was measured by hot air oven method as per ASTM, 2014 standards. 100g of tomato slice sample were kept inside hot air oven at 105°C for 24 hours [102]. The weight of the dried sample was measured on digital weighing machine at intervals of 5 hours. Based on the quantitative analysis, the initial moisture content was 94.7% wb. The reduction in the moisture of the tomato slices was determined by weighing the tomato slices every hour. Details of instruments used for tomato drying experiments has been displayed in Table 3.1.

The experiment was conducted from 9:30 to 16:30 hours for five times from 21st to 30th November 2021 in open sun drying and indirect type dryer domestic hybrid solar dryer (ITDHSD) system. Observation tables have been displayed in Appendix IV-VIII. During these initial winter season days, the conditions were similar and clear sky. Average values of experimental readings were taken for performance evaluation and have been shown in Table 3.2. All ambient parameters (solar insolation, relative humidity, ambient temperature, and air velocity), temperature readings, weight of tomato slices over the trays were noted at an interval of one hour during experimentation.

Instruments Used	Specification	Use	Accuracy
K-Type thermocouple sensors (Tempsens T-101)	0 to 400 °C	Temperature sensing	±1℃
Solar power meter (General tools DBTU-1300)	0 to 2000 W/m ²	Solar irradia- tion	± 10 W/m ²
Thermo-hygrometer (Testo-625)	0 to 100%	Relative hu- midity	±2.5%
Thermal anemometer (Testo-405)	0 to 10 m/s	Wind velocity	± 0.1 m/s
12-channel data logger (Sun Pro Instruments (In- dia))	-50 °C to +1210 °C	Temperature indicator	±0.5%
Weighing balance (Swisser SWIID06)	Up to 6 kg	Weight	±0.2 g

Table 3.1. Details of instruments used during the tomato drying experiments

	Ambient parameters							Data collected at various places inside the indirect domestic hybrid solar dryer												r		
	S.No.	Time	$\mathbf{I}_{\mathbf{g}}$	$\mathbf{I}_{\mathbf{d}}$	\mathbf{R}_{ha}	Ta	$\mathbf{V}_{\mathbf{a}}$	Vi	R _{he}	Ve	T ₁	T_2	T ₃	T ₄	T 5	T ₆	T ₇	T ₈	T9	T ₁₀	T ₁₁	T ₁₂
	1	09:30	432	70	52.7	294	0.15	0.1	30.5	3.66	294	297	305	309	311	302	309	308	305	306	306	305
	2	10:30	510	97	50.3	296	0.25	0.2	26.5	3.95	296	308	310	315	318	305	316	314	311	310	309	308
DAY 1	3	11:30	565	115	46.4	297	0.41	0.3	21.3	4.63	297	312	315	321	321	308	318	317	315	314	313	313
	4	12:30	620	126	43.6	298	0.33	0.4	19	4.13	300	315	320	326	324	311	321	319	317	315	314	314
	5	13:30	670	117	40.5	299	0.29	0.3	18.5	4.09	301	319	327	329	324	315	323	322	320	318	317	316
	6	14:30	645	109	43.4	299	0.4	0.3	18	3.71	300	316	324	324	321	310	321	320	318	316	315	314
	7	15:30	510	88	49	298	0.96	0.6	21.4	4.56	298	309	316	319	315	307	318	316	313	312	311	308
	8	16:30	424	80	50.2	297	0.51	0.3	26.6	4.02	297	301	312	317	312	301	315	314	312	310	309	307
	9	09:30	445	74	52.5	294	0.15	0.1	40.1	3.66	294	307	305	308	311	302	307	306	302	301	299	298
DAV 2	10	10:30	505	102	51.1	295	0.25	0.2	38.2	3.95	295	308	310	312	318	305	313	311	307	306	304	303
DAT 2	11	11:30	575	115	48.6	296	0.41	0.4	37.5	4.63	298	312	315	318	321	308	318	316	312	310	308	306
	12	12:30	630	118	47.1	298	0.33	0.4	37	4.13	300	315	320	322	324	311	322	321	317	315	313	311

Table 3.2. Mean reading values of tomato drying experiments performed from 21st November to 30th November 2021 in indirect domestic hybrid solar dryer

Where I_g is global solar radiation in W/m², I_d is diffused solar radiation in W/m², R_{ha} is relative humidity in %, T_a is ambient temperature in K, V_a is ambient air velocity at dryer's top surface in m/s, V_i is inlet air velocity in m/s, R_{he} is relative humidity at outlet of dryer in %, V_e is air velocity at outlet of the dryer in m/s, T_1 is Inlet air temperature, T_2 is Air temperature above collector surface, T_3 is Upper glass temperature, T_4 is Collector surface temperature 1, T_5 is Collector surface temperature 2, T_6 is Collector surface Temperature 3, T_7 is Collector outlet temperature, T_8 is temperature above tray1, T_9 is temperature above tray2, T_{10} is temperature above tray3, T_{11} is air temperature at the exhaust, T_{12} is temperature above the upper glass of dryer cabinet.

3.2.2. Performance Parameters

3.2.2.1. Moisture content (wb)

Moisture content wet basis of the crop can be determined as [103], [104]:

$$M_t = \frac{W_t - W_{dry}}{W_{total}} \tag{3.1}$$

3.2.2.2. Moisture ratio (MR)

It is the relation among moisture content present in the crop at any time 't' and initial moisture content of the food crop [22]. It can be calculated as:

$$MR = \frac{M_t - M_e}{M_i - M_e} \tag{3.2}$$

Equivalent moisture content M_e is an essential parameter in crop drying and cannot be neglected. It can be estimated using Halsey equation mentioned as [49], [105]:

$$RH = \exp\left(\frac{-11.08492}{RT_{absolute}} \times M_e^{-0.886330}\right)$$
(3.3)

To calculate equivalent moisture content of tomato slices, Eq. (3.3) can be simplified as [31], [49]:

$$M_e = \left[\frac{-11.08492}{RT_{absolute} \times \ln(RH)}\right]^{1.128}$$
(3.4)

3.2.2.3. Drying rate

The amount of moisture vaporized over a specific period is known as the drying rate. The expression for drying rate [22], [106] is given as:

$$D_r = \frac{M_i - M_{final}}{t} \tag{3.5}$$

3.2.2.4. Hourly drying efficiency

The hourly drying efficiency is a measure of how the indirect solar dryer works for maximum output with minimum energy input. It is the ratio of thermal energy utilized for moisture evaporation by the system to that of thermal energy collected by the solar collector at a particular interval. The expression is written as:

$$\eta_{i,dryer} = \frac{M_w \times l_w}{_{3600 \times A_{sc} \times I_{sc} \times t_i}} \tag{3.6}$$

3.2.2.5. Overall drying efficiency

Overall drying efficiency of the indirect type domestic hybrid solar drying (ITDHSD) system is the fraction of thermal energy utilized to vaporize moisture from the crop by the system to that of thermal energy accumulated by the solar collector [22], [107]. It is evaluated as:

$$\eta_{O,dryer} = \frac{l_w \sum_{i=1}^t M_w(t)}{_{3600 \times A_{SC} \sum_{i=1}^t I_{SC}(t)}}$$
(3.7)

3.2.2.6. Heat utilisation factor (H.U.F.)

It is the ratio of temperature reduction due to air cooling during drying and temperature raised due to air heating. It can be expressed as [80]:

$$H.U.F = \frac{T_{wf} - T_{cr}}{T_{wf} - T_a}$$
(3.8)

3.2.2.7. Coefficient of performance (C.O.P)

C.O.P of drying system can be given as [108]:

$$C.O.P = \frac{T_{cr} - T_a}{T_{wf} - T_a}$$
(3.9)

3.2.3. Statistical Analysis

Statistical analysis had also been performed based on the sum of squares due to error (SSE), R², adjusted R², and root mean squared error (RMSE) for validation of drying kinetics results of tomato slices. The equations of the methods, as mentioned above, are as follows [102], [109], [110]:

$$R^{2} = 1 - \frac{\sum_{i=1}^{n} (MR_{pre,i} - MR_{exp,i})^{2}}{\sum_{i=1}^{n} (MR_{exp,i})^{2}}$$
(3.10)

$$SSE = \sum_{i=1}^{n} (MR_{pre,i} - MR_{exp,i})^2$$
 (3.11)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (MR_{pre,i} - MR_{exp,i})^2}{n}}$$
(3.12)

$$(\bar{R})^2 = 1 - (1 - R^2) \frac{n_1 - 1}{n_1 - p_1 - 1}$$
(3.13)

where n_1 and p_1 are the number of repressors in the model and the sample size, MR_{pre} signifies the forecasted values, and MR_{exp} is the experimental values. The various selected drying models for this study are given in Table 3.3.

S. No.	Model name	Model	References
1	Lewis model	MR = exp(-kt)	[111]
2	Page model	$MR = exp(-kt^n)$	[112]
3	Henderson and Pabis model	$MR = a \exp(-kt)$	[113]
4	Two-term model	$MR = a \exp(-k_0 t) + b \exp(-k_1 t)$	[113]
5	Logarithmic model	$MR = a \exp(-kt) + c$	[102]
6	Wang and Singh model	$MR = 1 + at + bt^2$	[76]
7	Two-term expo- nential model	$MR = a \exp(-kt) + (1 - a)\exp(-kat)$	[76]
8	Verma et al. model	$MR = a \exp(-kt) + (1 - a)\exp(-gt)$	[76]
9	Prakash and Ku- mar	$MR = at^3 + bt^2 + ct + d$	[31]

 Table 3.3. Drying kinetic models

3.3. Results and Discussion

The sample crop used for experimentation was tomato, which contained about 94.7 % moisture content. Evenly sliced tomato weighing 1000g were used during open sun drying. 3000 g tomato slices were arranged in all three trays of ITDHSD as shown in Figure 3.1. The experimentation was performed in open sun drying mode and active mode drying in ITDHSD to get relevant results. The dried product of ITDHSD is displayed in Figure 3.2.



Figure 3.1. Labelled picture showing tomato slices kept on wire-mesh trays



Dried product from Tray 1

Figure 3.2. Labelled photo showing dried tomato in tray 1, tray 2 and tray 3

Experimentation of tomato slice drying was performed during winter month of

November 2021. The conditions during the experimentation were clear sky. Solar insolation and ambient temperature during experimentation varied between 424-670 W/m² and 294 – 299 K, respectively, as depicted in Figure 3.3.



From Figure 3.4, it can be noted that relative humidity and air velocity during the experimentation were in the range of 40.5% - 57.7% and 0.15-1 m/s, respectively.



Figure 3.4. Ambient air velocity and relative humidity Vs local time

Various graphs produced for ambient parameters during tomato drying, temperature variations recorded using K- type thermocouples inside ITDHSD during active mode experimentation can be seen in Figure 3.5. During both days, the maximum collector and drying cabinet temperature were observed as 311 K and 307 K, respectively.



Figure 3.5. Hourly temperature variation recorded at various places inside indirect type domestic hybrid solar dryer

The comparison of active mode and open sun drying is shown in Figure 3.6. The curve indicated that moisture content attained after 9 hours of drying is 10%, 11%, and 9% (wb) during active mode drying in ITDHSD. The low moisture content (9% wb) in each tray was attained after 10 hours of drying. The moisture ratio achieved was 0.095 after the specified time duration. In open sun drying, moisture content (wb) attained after 14 hours of drying was 14%, and further, no moisture removal took place from the tomato slices. The final moisture ratio during open sun drying achieved was 0.147 in 14 sunshine hours. Equivalent moisture content of tomato slices was calculated using Eq. 3.4 which was in the range of 2 - 0.13%. This was used for calculating moisture ratio.



Figure 3.6. Hourly moisture content (wet basis) trend of tomato drying under open sun and in indirect type domestic hybrid solar dryer

The drying kinetics and exergy analysis of the ITDHSD for tomato slices drying were analyzed using experimental observations. The average solar insulation during experimental days was 578 W/m². The uncertainties reported in the estimated parameters viz. moisture content, mass flow rate of air, exergy efficiency, dryer efficiency, and drying rate using Eq. (2.3) were ± 0.144 , ± 0.229 , ± 0.198 , ± 0.243 , and ± 0.179 respectively and these were in permissible limits.

The hourly drying rate trend was calculated using Eq. 3.5 for tomato crops placed inside the ITDHSD system and displayed in Figure 3.7. It was observed that the total moisture content mass of 2.84 kg out of 3 kg tomato was reduced to 270 g of moisture in 10 hours duration of drying in ITDHSD. The drying rate increased initially due to high free moisture content and internal heat generation, which led to a surge in internal temperature and steam pressure. Furthermore, this surge helped in

moisture diffusion to the surface, which resulted in a high drying rate. After 2 hours, the drying rate reduced gradually due to decreased availability of water molecules. The consequent reduction in drying rate suggested a high resistance to heat and mass transfer within the tomato crop material. Also, rapid evaporation of surface moisture resulted in the development of a solid layer on the surface of tomato slices, which obstructed the moisture evaporation, resulting in a low drying rate [114]. During day 1 the drying experiment was carried out for 7 hours and after that ITDHSD system was covered using polythene sheet. On day 2, a rise in the drying rate again was observed during the initial hour of drying, as shown in Figure 3.7. During final hours of drying, majority of water molecules were linked; therefore, drying rate was reduced again.



Figure 3.7. Hourly drying rate curve of tomato drying inside indirect type domestic hybrid solar dryer

The hourly global solar insolation was recorded hourly during the tomato slices drying experiment in ITDHSD using a solar power meter instrument. Other ambient parameters (ambient temperature, relative humidity, and air velocity) were also measured using thermohygrometer and thermal anemometer during the experiment conducted from 21^{st} to 30^{th} November 2021 from 09:30 to 16:30 hours. The hourly drying efficiency of ITDHSD ($\eta_{i,dryer}$) was calculated by using Eq. 3.6. The hourly drying efficiency was observed in a range of 4.04-68.78% and can be seen in Figure 3.8. Eq. 3.7 was used to evaluate the overall drying efficiency. It was observed that the overall drying efficiency of the ITDHSD was 41.05%. In the beginning, as the drying rate increased, the drying efficiency was observed to be higher, and it reduced after 11:30 hr as moisture evaporation was lowered and drying rate decreased gradually.



Figure 3.8. Hourly variation of drying efficiency and average hourly solar insolation falling over dryer during tomato drying in indirect type domestic hybrid solar dryer

Figure 3.9 shows the Heat Utilization Factor (HUF) and Coefficient of Performance (COP) of the drying system during the experimentation evaluated using Eqs.s 3.8 and 3.9. Heat utilization factor and COP for drying system were in the range of 0.59-0.84 and 0.16-0.44, respectively. Average heat utilization factor and coefficient of performance during experimentation for drying system were 0.67 and 0.33 respectively. It is evident from Figure 3.9 that the HUF increases gradually over time, as the temperature difference between the drying air and the wet crop decreases due to the reduction in moisture content. However, the heat supplied to

the dryer decreases with time due to the reduction in solar insolation. On the other hand, the COP decreases with time during the day, indicating that the energy efficiency of the system reduces as the day progresses. A similar trend can be observed on day 2. Prakash et al. [115] discussed variations of HUF and COP during crop drying.



Figure 3.9. Variation of heat utilisation factor and coefficient of performance with time during tomato drying experimentation

Figure 3.10 illustrates the assessment of moisture ratio of tomato slice drying with existing empirical relations. The X-axis implied the total time duration taken by the ITDHSD to achieve the required moisture ratio. For selection of a suitable drying model for drying kinetics of tomato, current drying curves as per moisture ratio were fitted along with nine separate existing drying models as presented in Table 3.2. The coefficient and constants of the models were calculated and stated in Table 3.3. This shows that all given models can predict the drying behaviour of crop slices. A model with lowest RMSE and SSE value and highest R^2 and adj. R^2 value describes the drying behaviour of crop slices. It had been noted that the Prakash and Kumar model provided a better correlation coefficient ($R^2 = 0.9991$ and Adj. $R^2 = 0.9989$) and lower reduced SSE= 0.001187 and RMSE = 0.01149, which indicated best fit as compared to other models. Thus, the Prakash and Kumar model was believed to be best fit model for tomato drying in indirect type domestic hybrid solar dryer. Drying equation for the evaluation of moisture ratio in tomato drying is written as Eq. (3.14).

$$MR = -0.00007978t^3 + 0.01392t^2 - 0.2321t + 1.031$$
(3.14)



Figure 3.10. Graph comparing the drying curve of tomato slices with predicted drying model.

Model	Tray	Model Constants	SSE	R ²	Adjusted R ²	RMSE
	Tray 1	k= 0.2816	0.03958	0.9684	0.9684	0.06291
Lewis	Tray 2	k= 0.2543	0.05282	0.9584	0.9584	0.07268
	Tray 3	k= 0.2975	0.03718	0.9703	0.9703	0.06098
	OSD	k= 0.1066	0.02775	0.9745	0.9745	0.02991
	Tray 1	k= 0.1495, n= 1.449	0.006454	0.9948	0.9926	0.03036
Page	Tray 2	k=0.1172, n=1.522	0.007841	0.9938	0.9912	0.03347
	Tray 3	k=0.1622, n=1.444	0.006194	0.9951	0.9929	0.02975
	OSD	k= 0.0942, n= 1.062	0.01256	0.9885	0.9856	0.03236
	Tray 1	k= 0.3024, a= 1.082	0.02952	0.9764	0.9738	0.05727
Henderson and Pabis	Tray 2	k= 0.2763, a= 1.094	0.03892	0.9694	0.966	0.06576
Thenderson and Tabis	Tray 3	k= 0.3182, a= 1.078	0.02823	0.9775	0.975	0.056
	OSD	k= 0.1105, a= 1.029	0.02568	0.9764	0.9747	0.04283
	Tray 1	k ₀ =0.5518, a=18.15, b=-17.15, k ₁ =0.5819	0.001398	0.9989	0.9984	0.01413
Trans (and	Tray 2	$k_0=0.5058$, $a=7.814$, $b=-6.818$, $k_1=0.5828$	0.002271	0.9982	0.9974	0.01801
I wo term	Tray 3	k ₀ =0.629, a=-11.09, b=12.09, k ₁ =0.5794	0.001279	0.999	0.9985	0.01352
	OSD	$k_0=0.1437$, $a= 6.81$, $b= -5.791$, $k_1=0.1511$	0.02337	0.9785	0.9732	0.04413

Table 3.4. Statistical results for various thin layer models available for tomato drying

	Tray 1	k= 0.2185, a= 1.208, c= -0.1584	0.01227	0.9902	0.9877	0.03917
Logarithmic	Tray 2	k= 1793, a= 1.291, c=-0.2363	0.01472	0.9884	0.9855	0.04289
Logartinito	Tray 3	k= 0.2395, a= 1.182, c= -0.1323	0.01313	0.9895	0.9869	0.04051
	OSD	k= 0.06449, a= 1.363, c= -0.3708	0.01744	0.984	0.9815	0.03663
	Tray 1	a= -0.2059, b= 0.01072	0.008284	0.9934	0.9926	0.03034
Wang and Singh	Tray 2	a= -0.186, b= 0.008617	0.01244	0.9902	0.9891	0.03718
	Tray 3	a= -0.2167, b= 0.01186	0.007641	0.9939	0.9932	0.02914
	OSD	a= -0.08468, b= 0.001871	0.01982	0.9818	0.9805	0.03763
	Tray 1	a=2.008, k=0.4382	0.001764	0.9986	0.9984	0.014
Two term exponential	Tray 2	a=2.052, k= 0.4063	0.003133	0.9975	0.9973	0.01866
I I I I I I I I I I I I I I I I I I I	Tray 3	a= 2.003, k= 0.4063	0.001721	0.9986	0.9985	0.01383
	OSD	a= 1.618, k= 0.139	0.02251	0.9793	0.9778	0.0401
	Tray 1	a= -27.06, k= 0.5856, g= 0.5655	0.001345	0.9989	0.9987	0.01297
Verma et al.	Tray 2	a= -8.72, k= 0.5674, g= 0.5083	0.00229	0.9982	0.9977	0.01692
	Tray 3	a= 21.39, k= 0.5865, g= 0.6136	0.001283	0.999	0.9987	0.01266
	OSD	a= -5.843, k= 0.1692, g= 0.1575	0.02233	0.9795	0.9763	0.04145
	Tray 1	a= 0.00001361, b = 0.01149, c = -0.2175, d= 1.032	0.001346	0.9989	0.9988	0.01223
Prakash and Kumar	Tray 2	a= 0.0003932, b = 0.004104, c = -0.1809, d= 1.032	0.001891	0.9985	0.9983	0.0145
	Tray 3	a= -0.00007978, b = 0.01392, c = -0.2321, d= 1.031	0.001187	0.9991	0.9989	0.01149
	OSD	a= -0.0002676, b= 0.007637, c= -0.1149, d= 1.018	0.02275	0.9871	0.98679	0.04031

A comparative study of tomato drying in ITDHSD was performed with existing tomato drying studies. Comparison of various tomato dryers in drying time and final moisture content (% wb) is displayed in Figure 3.11. Conventional hot air blower tomato drying conducted by Mariem and Mabrouk [114] reduced moisture content of tomato to 11% in 9.9 hours. Abuelnuor et al. [94] performed experimental study on tomato drying using indirect and mixed mode solar dryer. The final moisture content of 10.4% was achieved during 10 hours and 9 hours, respectively. A ITSD system proposed by Lingayat et al. [102] dried tomato to final moisture content of 29.5% in 10 hours. It had been observed that ITDHSD had achieved 9% final moisture content in 10 hours of drying. It had been concluded from this comparison that ITDHSD had attained relatively smaller final moisture content in less time duration.



Figure 3.11. Comparison of various tomato dryers in terms of drying time and final moisture

content

3.4. Summary

An experiment to dry tomato slices in ITDHSD and open sun was conducted at Delhi Technological University, Delhi, India, during winter season five times from 21st to 30th November 2021. Following conclusions have been made from the above results and discussion:

- Initial moisture in the tomato slices was reduced from 94.7 % (wet basis) to 9% (wet basis) in 10 hours drying in the ITDHSD and to 14% (wet basis) in open sun drying in 14 hours of drying.
- The maximum drying rate was found to be 0.47 kg of water/hour.
- Overall drying efficiency of the ITDHSD system was 41.05% and hourly drying efficiency was in the range of 4.04-68.78%.
- Heat utilization factor and COP for ITDHSD were in the range of 0.59-0.84 and 0.16-0.44, respectively.
- Prakash and Kumar model was found best fit for tomato drying in ITDHSD.
- ITDHSD dried tomato slices achieved good sensory quality than the open sundried tomato slices.
- ITDHSD had attained relatively smaller final moisture content in less time duration as concluded from the comparative study of tomato drying with conventional dryer and several solar drying systems.

ITDHSD was found to be more efficient as it dried tomato slices in 10 hours while during open sun drying, 14% of moisture content was achieved after 14 hours of drying. Furthermore, drying of food inside ITDHSD has been more consistent and this will result in better quality of dried products than open sun drying.

In the next chapter, 3E analysis (exergy, energy, economic) and quality of dried tomato crop in indirect domestic hybrid solar dryer have been investigated and discussed.
CHAPTER-IV

EXERGY, ENERGY, ECONOMIC (3E) ANALYSIS AND QUALITY ASSESSMENT OF SOLANUM LYCOPERSICUM (TOMATO) DRYING IN INDIRECT TYPE DOMESTIC HY-BRID SOLAR DRYER (ITDHSD) SYSTEM

4.1. General Introduction

Crop drying is essential for food processing and preservation [29]. Drying removes moisture from crop and enhances its lifespan [116]. Food drying is commonly performed using conventional dryers that run over high-grade electrical energy [45]. This energy is generally produced by combustion of fossils and this combustion causes emission of greenhouse gases such as CO₂ into the environment [3]. Furthermore, this usage of electrical energy is costly. Therefore, solar food drying is encouraged among users. A general method of solar food drying is open sun drying. It is free of cost and has no greenhouse gas emissions from this method, but it has some disadvantages [62]. Food is kept open in the environment, which increases the chances of deterioration of food quality and the efficiency of this process is very low [117]. To address these issues originating from conventional drying and open sun drying, the usage of dedicated devices named solar food dryers is encouraged.

Solar food dryers are more efficient than open sun drying due to controlled environment drying. During operation, these have zero greenhouse gas (GHG) emissions [118]. Moreover, it is more economical than conventional dryers in terms of initial and operating costs [119]. Solar food dryers can be used for food drying applications in domestic, medium, and small-scale as well as large-scale industries [120]. Solar dryers are preferable for crop drying due to their better efficiency than open sun drying. Although the dryers didn't use any conventionally produced energy during operation, preparation of material used in dryer fabrication can be manufactured using conventional energy. This conventional energy used for dryer fabrication is termed embodied energy and generation of this conventional energy releases significant amount of GHGs (primarily CO₂). Embodied energy and CO₂ released should be accounted and to become environmentally friendly devices, solar dryers should save at least energy equal to their embodied energy and mitigate CO₂ which was used during their fabrication. Several studies have been carried out on different solar dryers for performance and environmental analysis such as energy payback time (EPBT) and CO₂ mitigation which have been tabulated in Table 1. Concluding remarks of each study have been discussed as follows:

Simple and modified greenhouse dryer performance, EPBT, CO₂ mitigation, and total carbon credit were evaluated and compared for groundnut drying, and modified dryer was found superior [121]. Gupta et al. [122] performed sustainability and 4 E analysis on a solar photovoltaic thermal dryer. Mugi and Chandramohan [123] performed exergy analysis on an indirect type solar dryer. Performance parameters and drying kinetics of heat exchanger-evacuated tube assisted drying system for drying garlic was evaluated and overall drying efficiency of drying system was observed as 25.1% [124]. Tomato crop was dried in a hybrid active greenhouse solar dyer integrated with evacuated solar collector. Payback period and CO₂ mitigation were reported as 1.73 years and 169.10 Tonnes, respectively [125]. Overall drying efficiency of indirect type solar dryer (ITSD) was reported as 31.42% [102]. Large-scale solar dyer integrated with phase change material had EPBT 6.82 years and lifetime CO₂ mitigation of 99.60 Tonnes [126]. EPBT for an indirect solar dryer used for drying bitter gourd was reported as 2.21 years and CO₂ mitigation assessed for lifetime of the system was 33.52 years [49]. Sajith and Muraleedharan (2020) reported payback period, benefit-cost ratio, and EPBT as 9.3 years, 1.61, and 2.25 years for indirect solar dryer embedded with hybrid photovoltaic thermal air heater for drying amla (Phyllanthus emblica Linn) [50]. The embodied energy, EPBT, and carbon credit of a domestic direct type multi-shelf solar dryer were stated as 339.015 kWh, 7.57 years, and INR 2055, respectively [62].

A convective dryer used for drying wood chips had drying chamber's universal exergy efficiency from 41.84% to 98.07%, and drying system's average overall exergy efficiency varied from 1.32% to 4.01% [127]. A thermo-environomical assessment of a north wall insulated greenhouse dryer under natural and forced mode drying gave EPBT as 1.68 years and 2.35 years, net Carbon dioxide mitigation as 33.04 and 36.34 Tonnes, respectively [103]. Embodied energy, EPBT, and CO₂ mitigation of an indirect solar drying system were 1081.83kWh, 4.36 years, and 391.52 kg per year, respectively for drying fenugreek [52]. For potato drying in modified solar greenhouse dryer during active and passive mode drying, the corresponding values of payback period and earned carbon credits were 1.9 years, 1.25 years, and INR 37,826 and INR 37,882 [128]. Payback period, embodied energy, and EPBT were reported as 1.9 years, 628.7287 years, and 1.14 years, respectively

for tomato drying in modified greenhouse dryer [76]. Payback period of indirect type solar dryer for bitter gourd drying was estimated as 3.26 years [53].

Agricultural products can be preserved via solar drying, which also lowers postharvest losses and boosts food security. The environmental and financial viability of various solar drying systems, however, is still a subject of interest and research. While earlier studies have evaluated the environmental and economic factors of various solar dryers. However, most research has focused on greenhouse-type, direct-type, and flat-plate collector-based indirect-type solar dryers. Surprisingly, no studies have investigated the environmental and economic feasibility of indirect domestic hybrid solar dryers for tomato crop drying. Additionally, previous evaluations of exergy and embodied energy in solar dryers did not consider the PV module's embedded energy. This chapter aims to fill this research gap by focusing on a unique PV-integrated compact hybrid solar dryer with a rectangular corrugated collector suitable for domestic and small-to-medium-scale industrial applications. The study investigates the exergy, environomical factors, and economic viability (3Eanalysis) of an indirect-type domestic hybrid solar dryer (ITDHSD) for tomato drying. Furthermore, the study includes quality analysis viz. sensory analysis, rehydration ratio, shrinkage, and hardness, to evaluate the dried product outcomes from ITDHSD.

This study's novelty and significance come from its contribution to the development of environmentally friendly and economically viable drying systems for agricultural products. This work provides insights on the performance and feasibility of a novel drying technology for tomato crops by concentrating on a unique PV-integrated compact hybrid dryer. A comprehensive analysis of the ITDHSD's performance is also provided by the inclusion of quality analysis, which may be used to design and execute high-quality, sustainable drying systems for different food products. Finally, this investigation gives more precise assessment of the environmental impact of solar drying systems by taking into account the embedded energy in PV modules. The results of this study have major repercussions for post-harvest loss reduction, lowering the carbon footprint of the food industry, and sustainable food production.

4.2. Materials and Method

4.2.1. Exergy analysis

Exergy of any system can be determined utilizing the qualities of working fluid using first law energy balance. Equation to determine exergy relevant for a steady flow system is as follows [129]:

$$Ex = \dot{m}_a c_{pa} [(T - T_a) - (T_a \ln \frac{T}{T_a})]$$
(4.1)

In the case of indirect type domestic hybrid solar dryer, exergy input is given as:

$$Ex_i = Ex_{sci} + Ex_{PV} \tag{4.2}$$

Where Ex_{sci} is inflow in drying chamber which is written as:

$$Ex_{sci} = \dot{m_a}c_{pa}[(T_{sc} - T_a) - (T_a \ln \frac{T_{sc}}{T_a})]$$
(4.3)

and Ex_{PV} is exergy of PV module mounted over the drying cabinet of the indirect type domestic hybrid solar dryer to run the fan which is given as [68]:

$$Ex_{PV} = \eta_{PV} \times (IA)_{PV} \tag{4.4}$$

Entire exergy output from ITHSD is determined as:

$$Ex_o = Ex_{sco} + Ex_w \tag{4.5}$$

Where Ex_{sco} is exergy outflow from drying chamber which is given as [130], [131]

$$Ex_{sco} = \dot{m_a}c_{pa}[(T_{dc} - T_a) - (T_a \ln \frac{T_{dc}}{T_a})]$$
(4.6)

and Ex_w is the exergy of work rate due to PV module and DC fan work which is given as:

$$Ex_w = W = (I_{sc} \times V_{OC}) - (I_L \times V_L)$$
(4.7)

Exergy losses during the solar drying process using values of exergy input and output is calculated as [129]:

$$Ex_{loss} = Ex_{sci} - Ex_{sco} \tag{4.8}$$

Exergy efficiency can be determined as the fraction of exergy invested in the drying of the crop to the exergy of the drying working fluid (air) provided to the system. It is calculated as:

$$\eta_{ex} = \frac{Ex_{sco}}{Ex_{sci}} = 1 - \frac{Ex_{loss}}{Ex_{sci}} \tag{4.9}$$

4.2.2. Sustainability indicators

These are the parameters that identify the effect of exergy loss and efficiency over sustainable drying process development. These indicators are beneficial for attaining more sustainable, environmentally, economical, and efficient energy utilization in the drying systems. Vijayan et al. (2020) mentioned that system sustainability varies with air mass flow rate and temperature. The sustainability indicators evaluated in this piece of work are IP (improvement potential), WER (waste exergy ratio), and SI (sustainability index). The sustainability indicators behave similarly to the exergy efficiency and are given as [126], [132], [133]:

4.2.2.1.Improvement potential (IP)

It is a sustainability indicator used to determine the effect of exergy efficiency and exergy loss over the continual development of the solar crop drying process. It is given as:

$$IP = (1 - \eta_{Ex})Ex_{loss} \tag{4.10}$$

4.2.2.2.Waste exergy ratio (WER)

It is a sustainability indicator. It is used to determine the consequence of exergy loss over the sustainable development of the solar crop drying process and is given as:

$$WER = \frac{Ex_{loss}}{Ex_{sci}} \tag{4.11}$$

4.2.2.3.Sustainability index (SI)

It is used to determine the consequence of exergy efficiency over the sustainable development of the solar crop drying process. It is determined as:

$$SI = \frac{1}{1 - \eta_{ex}} \tag{4.12}$$

4.2.3. Energy assessment of the indirect type domestic hybrid solar dryer (ITDHSD)

Energy assessment is a study that contemplates on surge in fuel prices, raw materials, and environmental impact. Thus, it is essential to conduct energy assessment for the drying system. Energy assessment for indirect type domestic hybrid solar dryer (ITDHSD) includes the assessment of embodied energy, energy payback time (EPBT), yearly CO₂ emissions, carbon mitigation, and carbon credit.

4.2.3.1.Embodied energy

The energy desired for manufacturing objects, services, or things is depicted as embodied energy [62]. It can be called an indication of the global environmental impact of systems and materials. The consumption of energy generates CO_2 , which adds emissions of greenhouse gases. It is an essential factor to study in the assessment of life cycle of a product and it relates straight to sustainability of built environment.

4.2.3.2. Energy payback time (EPBT)

Energy payback time is the time it takes for a product, service, or thing to recover its embodied energy [62], [113]. It is an important factor to evaluate viability of any product by considering payback of energy consumed during its production. It can be assessed as [134]:

$$EPBT = \frac{Embodied \, Energy}{Annual \, Energy \, Output} \tag{4.13}$$

4.2.3.3.CO₂ emissions

Throughout the process of coal-based electricity generation, average emission of CO_2 is equivalent to 0.98 kg CO_2 /kWh [135]. Hence, yearly CO_2 emissions can be assessed as [134]:

$$CO_2 \text{ emissions per year} = \frac{Emboided \text{ energy} \times 0.98}{Lifetime}$$
 (4.14)

4.2.3.4. Carbon mitigation and earned carbon credit

Climate change potential is measured as Carbon mitigation. The net CO_2 mitigations are examined per kilowatt-hour; hence, its comparison with other power production systems is extremely possible. In ITDHSD, CO_2 mitigation is evaluated. The carbon credit is termed an essential factor of national and international emissions trading programs that have been applied to mitigate- global warming [76]. Purchasing and trading carbon credits on a global market or in a corporation are currently possible. It applies to monetary carbon reduction initiatives.

System's daily efficiency can be considered as [103]:

$$\eta_{daily} = \frac{daily \ output \ energy}{daily \ input \ energy} = \frac{E_{do}}{E_{di}} \times 100 \tag{4.15}$$

Dryer's daily thermal output (E_{do}) in kWh can be evaluated [62]:

$$E_{do} = \frac{M \times \lambda_w}{3.6 \times 10^6} \tag{4.16}$$

Daily input energy (E_{di}) can be computed as [52]:

$$E_{di} = I_m(t) \times N_h \times A \times 10^{-3} \tag{4.17}$$

Dryer's yearly energy output (E_y) can be given as [31]:

$$E_y = E_{do} \times N_d \tag{4.18}$$

The transmitted power is equal to $\frac{1}{1-L_t}$ Units when all energy losses by the end-user in domestic equipment (Lt = 10%) are taken into account. In distribution and transmission, there is an L_{dt} (45%) loss of energy per unit. As a result, the

amount of energy produced by a power plant can be expressed as $\frac{1}{1-L_t} \times \frac{1}{1-L_{dt}}$ Units [62].

Given that coal-based energy has an average carbon dioxide equivalent intensity of 0.98 kg of CO₂/kWh, the system's overall CO₂ mitigation (X_m) is as follows [62]:

$$X_m = \frac{1}{1 - L_t} \times \frac{1}{1 - L_{dt}} \times 0.98 = 2.01$$
 kg/unit

The CO₂ mitigation can be calculated as [49]:

$$CO_2$$
 mitigation during life of solar dryer = $E_y \times X_m$ (4.19)

Hence, net mitigation of CO_2 during lifetime (kg) = Total CO_2 mitigation – Total CO_2 emissions.

Net mitigation of
$$CO_2$$
 during lifetime $(kg) = E_y \times n \times X_m - E_m$

$$(4.20)$$

Earned Carbon credit = net mitigation of CO_2 during lifetime (kg) × D_c (4.21)

4.2.4. Economic Analysis

The economic analysis of the indirect type domestic hybrid solar dryer is important as it directly comprises the financial traits for commercial application. The cost of an indirect solar dryer is assessed by taking the totality of the cost of materials utilized in the construction of the dryer and working capital cost [69]. The payback period of the dryer is defined as the time required to recover the original cash investment and it is evaluated as [69]:

Payback period
$$= \frac{C_{initial}}{P_{net}}$$
 (4.22)

where,

Net profit (P_{net}) is the total income obtained excluding the working capital cost and can be depicted as [69]:

$$P_{net} = Gross income - working capital cost.$$

The quantity of annually dried tomato flakes (DT_{annual}) is considered as the product of the mass of dried tomato per hour with total sunshine hours for it [31].

$$DT_{annual} = T_t \times D_s \tag{4.23}$$

According to climatic conditions in Delhi (India), the average yearly sunny days are 250 and the average annual sunshine hours are 1500. The sale price of dried products is considered as per present market rates.

4.2.5. Quality assessment of tomato flakes

The quality characteristics of the dehydrated tomato flakes are assessed in terms of sensory analysis, rehydration ratio, shrinkage, and hardness. Further, it is compared with the open sun-dried tomato flakes.

4.2.5.1.Sensory Analysis

Sensory analysis criteria such as color, taste, flavor, mouth feel, appearance and overall acceptance were used to assess the quality of dried tomato flakes produced by drying in the open sun and ITDHSD [90], [136]. Forty untrained panelists were chosen among the university's academic personnel, students, and technicians. The panelists rated the dried samples for color, taste, mouth feel, appearance, flavor, and overall acceptance of dried tomato flakes using a five-point hedonic scale, with '1' being severely disliked and '5' being extremely liked. The dried samples were coded and placed at random. After evaluating each sample, panelists were told to rinse their mouths out with water before moving on to the next.

4.2.5.2. Rehydration ratio

To evaluate the rehydration ratio of tomato flakes, a 10 g dried tomato slice sample was used and boiled in water with 1% salt content for 10 minutes, and then the final weight was observed [103]. The rehydration ratio is estimated using the following equation:

Rehydration ratio
$$=\frac{m_{final}}{m_{initial}}$$
 (4.24)

4.2.5.3.Shrinkage

Shrinkage is the difference in volume between dried tomato flakes and fresh tomato flakes expressed as a percentage [103]. It is given as follows:

Percentage of shrinkage =
$$\frac{(V_{actual} - V_{final})}{V_{final}} \times 100$$
 (4.25)

4.2.5.4.Hardness

Hardness is one of the most significant characteristics in the quality evaluation of dried tomato flakes. It is the most significant force applied during the first bites observed in grams. The hardness of the dried tomato flakes was studied next to rehydration, using the CT3 Texture Analyser [103], [137]. The result of hardness was concluded by taking an average of 10 observations.

4.3. Results and Discussion

4.3.1. Exergy analysis and sustainability indicators

Figure 4.1 shows the dryer exergy outflow, inflow, and loss in drying cabinet with mass flow rate variations during tomato slice drying experimentation calculated using Eqs.s (4.3), (4.6) and (4.8). The temperature and air velocity were significant design factors for drying food crops. The air velocity decreased right away after entering the drying cabinet due to increased system volume. The exergy analysis was necessary to recognize the operational circumstances' improvement potential. The exergy of the PV module was also included while estimating the exergy of the ITDHSD system. It was noticed that exergy enhanced gradually during starting hours and surged as mass flow rate in the system increased. The exergy peak had been seen where mass flow rate in the system was higher.



Figure 4.1. Exergy variation during tomato drying in indirect type domestic hybrid solar dryer with varying mass flow rate

Figure 4.2 shows the variation of exergy efficiency with the mass flow rate variation in the system. The exergy efficiency of the ITDHSD during tomato drying showed that exergy efficiency surged with an increased mass flow rate of drying air. This was due to a lower temperature difference between air entering and leaving the drying cabinet unit. Similar kinds of variations were reported by Colak and Hepbasli (2007). The average exergy loss and exergy efficiency estimated using Eq. (4.9) during the tomato drying experimentation in ITDHSD were 56.56 W and 46%, respectively.



Local Time (Hours) Figure 4.2. Exergy efficiency variation of indirect type domestic hybrid solar dryer with varying mass flow rate during tomato drying

Exergy sustainability indicators were estimated using Eqs. (4.10) - (4.12) and displayed in Table 4.1 for tomato drying experimentation in ITDHSD. The improvement potential for tomato drying varied from 0.006966-0.065984 kW. It increased with higher mass flow rate value, which showed the possibility of improving the drying process by increasing drying air temperature. The sustainability index had been expressed in terms of exergy efficiency, which was 1.55 - 2.39. It surged with increased drying air's mass flow rate due to higher exergy efficiency during tomato drying experimentation. The waste exergy ratio (WER) varied between 0.41-0.67. The WER values should lie between 0 and infinity [132]. The lower WER values showed that exergy loss was lower.

Day	Time (hr)	IP	W	SI
	09:30	0.009522	0.577231	1.732409
	10:30	0.012758	0.59671	1.675856
	11:30	0.026192	0.644414	1.551797
Day 1	12:30	0.00985	0.469836	2.128401
Day 1	13:30	0.065984	0.566732	1.764502
	14:30	0.061199	0.577472	1.731685
	15:30	0.064198	0.437054	2.288049
	16:30	0.031461	0.574835	1.739629
	09:30	0.014085	0.67141	1.489402
Day 2	10:30	0.006966	0.445057	2.246904
	11:30	0.009812	0.456222	2.191915
	12:30	0.040517	0.417381	2.395895

Table 4.1. Calculated sustainability indicators for tomato drying experimentation in ITDHSD

4.3.2. Embodied energy analysis

The embodied energy of the indirect type domestic hybrid solar dryer (ITDHSD) and coefficient of embodied energy for various items utilized in the fabrication of dryer are displayed in Table 4.2. The overall embodied energy for the fabrication of the ITDHSD was estimated as 1434.2 kWh. Daily output and input energy calculated using Eqs.s (4.10) and (11) for ITDHSD for tomato drying were 1.3623 kWh and 1.9145 kWh, respectively. The daily efficiency of ITDHSD was estimated using Eq. (4.15) and found to be 71.16%. Annual energy output was assessed 340.6 kWh/year from Eq. (4.18), considering 250 sunshine days in a year.

S.No.	Items	Embodied en- ergy coefficient (kWh/kg)	Amount (kg)	Total embod- ied energy (kWh)	Reference
1	Glass sheet	7.28	20	145.6	
2	Iron angles	9.72	26	252.7	[52], [139]
3	FRP Sheet	41.67	1.5	62.51	
4	GI Sheet	9.67	2	19.34	
5	Stainless steel wire mesh	8.89	0.5	4.45	[139]
6	Plywood	2.89	15.5	44.8	•
7	Fan	19.44	0.15	2.92	[128]
8	Aluminium frame	55.28	0.4	22.1	[139]
9	Glass wool	4.06	0.8	3.3	[103]
10	Rubber seal	30.56	0.8	24.5	
11	Aluminium Sheet	55.28	1.5	82.92	[120]
12	Paint (solvent based)	27.25	1	27.25	. [139]
13	Polystyrene	32.5	0.122	3.97	•
14	Copper wire	19.61	0.2	3.92	
15	Fittings		1.2	47.99	•
16	Solar PV module 20 W,12V			607	[128], [140]
17	Battery	148.45		46	
18	Solar charge con- troller			33	
Total				1434.2	kWh

Table 4.2. Embodied energy of different materials used in fabrication of ITDHSD system

The EPBT calculated using Eq. (4.13) for ITDHSD was 4.21 years. Evaluated quantity of carbon dioxide emissions during the fabrication of the ITDHSD system was 1405.5 kg. The net CO₂ mitigation for tomato flakes drying by ITDHSD during its estimated lifetime of 20 years was computed using Eq. (4.20) as 12.28 Tonnes. The earned carbon credit for ITDHSD system for tomato drying was calculated. The present rate of carbon credit is US \$30.83/Tonnes (carboncredits.com). The computed value for earned carbon credit by ITDHSD for tomato drying has been noted as US \$364 (US \$1 = ₹81.84 as of 09/04/2023).

The contribution of materials used for fabrication of ITDHSD in total embodied energy can be seen in Figure 4.3. The value of EPBT was observed to be less as compared with lifetime of ITDHSD, which signifies that the fabricated dryer is economical. It saves more energy during operation than the energy consumed by different materials used during its fabrication. Carbon mitigation shows a way to restrict the impact of greenhouse effect emissions on a commercial scale by capping aggregate yearly emissions and giving a chance to compensate for any shortage of allotted mitigation of greenhouse gas emissions. ITDHSD can save 12.28 Tonnes of CO₂ emissions, which helps sustain the environment.



Total embodied energy (kWh)

Figure 4.3. Contribution graph embodied energy of material utilized for constructing ITDHSD

system

4.3.3. Economical analysis

Table 4.3 presents the economic evaluation of the ITDHSD system for drying tomato flakes. Total initial capital for fabrication of ITDHSD system was US \$245 (₹20,350). Operating cost of ITDHSD for tomato drying throughout the year (considering 250 sunshine days) was estimated US\$ 563 (₹46,770). The operator purchased 3 kg raw material (tomato) from a nearby vegetable market for dried crops and further washed and sliced. It took 10 hours to dry a single batch of 3 kg crop. Therefore, in a year, 530 kg of tomato can be dried, providing dried tomato flakes of 71 kg per year. This dried tomato can easily be sold at US\$ 14-\$38 (₹1200-₹3150) per kg at local markets and online market platforms. Net profit from selling the dried product at minimal selling price of \$14.66/kg (₹1200/kg) was estimated \$478 (₹39700).

Furthermore, ITDHSD system's payback period was computed using Eq. (4.22) as 6 months because the initial capital was minimal. Since ITDHSD's payback period is far shorter than its projected lifespan of 20 years, tomato slice drying can be done for free for 95% of its useful life. ITDHSD was constructed with the support of locally skilled laborers and materials were procured from the local market. This makes ITDHSD economical in terms of initial capital cost. Furthermore, operating cost of ITDHSD, which comprised all expenses, including raw material and operator cost was less. ITDHSD provides high-quality dried products that can be sold at high cost at local and online marketplaces. Therefore, ITDHSD covers its initial capital quickly and can generate employment and livelihood in small and medium scale industries.

Parameter	Value
Initial capital (Cost of ITDHSD system)	\$245 (₹20350)
Operating cost	
I. Raw Material @ \$0.37/kg for 530 kg	\$196 (₹16285)
I. Maintenance and repair cost @ 10% of initial capital	\$25 (₹2035)
III. Labour cost @ \$1.22/day for 250 days	\$305 (₹25340)
IV. Packaging charge	\$37 (₹3075)
Total Operating cost (I+II+III+IV)	\$563 (₹47750 approx.)
Selling price of dried product @ \$14.66/kg for 71 kg	\$1041 (₹86500)
Net annual income	\$478 (₹39700)
Simple payback period	6 months 3 days
Life of solar dryer	20 years
Loading capacity	3 kg
No. of working days	250 days
Total dried tomato flakes per year	520kg

 Table 4.3. Economic investigation of tomato drying in drying system

4.3.4. Quality assessment

The accessed sensory attributes of open sun dried and ITDHSD dried tomato slices are exhibited in Fig. 4.4. Panel members provide better scores for the sample dried through ITDHSD than open sun-dried samples. The scores of ITDHSD dried tomato samples were better in all the attributes such as colour, flavour, mouthfeel, taste, and appearance. For color and mouthfeel, have high differences in the scores among dried produce from ITDHSD and open sun. Overall acceptability of ITDHSD dried tomato slices was 4.2 which is higher than open sun-dried tomato slices.



Figure 4.4. Comparison of sensory attributes of tomato slices dried under ITDHSD and open sun

Rehydrated tomato slice observations are provided in Table 4.4. Rehydration is an essential parameter of effective drying. Tomato has a good rehydration capacity. The flakes dried through ITDHSD during active mode had a higher rehydration capacity than flakes dried under open sun. Tomato flakes with 14% final moisture content, which dried under the open sun shrunk radially and uniformly, while the flakes have lower moisture content i.e., those dried in the ITDHSD revealed a shrivelled appearance with uneven curling. Moreover, the hardness of dried tomato flakes was found greater due to controlled airflow in ITDHSD. Open sun-dried tomato flakes were softer than dried flakes obtained from ITDHSD as the removal of moisture in open sun was less. Obtained values for the shrinkage and hardness have been summarized in Table 4.4.

Variations in the moisture content, pressure, and temperature gradient during drying resulted in generation of contractile stresses in tomato flakes. Majumdar et al. [141] discussed the reason for shrinking and hardening of crop during drying. Flakes dried inside the drying system had lost high moisture content than open sun drying. Therefore, Tomato flakes dried inside ITDHSD dryer had a higher shrinkage value (74%) than those dried in open sun. Furthermore, hardness of dried tomato flakes obtained from ITDHSD was comparatively higher (171g) than open sun drying. The color of the dried product in the ITDHSD system was nearer to the original color than the product dried under open sun. The color of dried tomato flakes under open sun faded because of the loss of volatile contents due to the direct fall of solar radiation over tomato flakes. The ITDHSD gave superior quality dried products due to favorable drying conditions inside the dryer.

Parameters	Open Sun Drying	ITDHSD
Shrinkage (%)	68	74
Rehydration ratio (g of water in 10 g of dried sample)	12.5	15.8
Hardness (g)	140	171

Table 4.4. Results of quality estimation of dried tomato flakes

4.4. Comparison with existing drying systems

A comparison of ITDHSD with existing solar drying systems has been reported in Table 4.5. Modified and Simple convection greenhouse dryers had overall drying efficiency of 26.23% and 23.34%, with total CO₂ mitigation of 1.45 and 1.26 Tonnes, respectively [121]. Heat exchanger- evacuated tube assisted drying system had dryer efficiency of 25.1% [124]. Indirect solar drying unit had an efficiency of 31.42% and EPBT of 4.36 years. It mitigated 7.83 Tonnes of CO₂ in 20 years [52]. An ITSD system had a drying efficiency of 31.4% for tomato slices drying [102]. The present ITDHSD system is superior in terms of overall drying efficiency, which was 41.05% [82]. Total CO₂ mitigated by ITDHSD was 12.28 Tonnes.

Drying System	Overall drying ef- ficiency (%)	EPBT (Years)	Total CO2 mitigation (Tonnes)	References
Modified convection green- house dryer	26.23	2.28	1.45	[121]
Simple convection greenhouse dryer	23.34	1.27	1.26	[121]
Heat exchanger- evacuated tube assisted drying system	25.1	-	-	[124]
Indirect solar drying unit	31.42	4.36	7.83	[52]
Indirect type solar dryer (ITSD) system	31.4	-	-	[102]
ITDHSD system	41.05	4.21	12.28	Present system

Table 4.5. Comparison of ITDHSD with existing solar drying systems

4.5. Summary

Tomato drying experimentation in ITDHSD system was performed at Delhi Technological University (DTU), Delhi, India, in November 2021 (winter). The following conclusions have been drawn from the present work:

- Exergy efficiency of the ITDHSD system varied from 32.86% to 58.26% and overall exergy efficiency was 46%.
- Exergy sustainability indicators viz. IP (improvement potential) varied from 0.006966-0.065984 kW, WER (waste exergy ratio) varied from 0.41-0.67 and SI (sustainability index) varied from 1.55 2.39.
- Embodied energy in fabrication of ITDHSD system was evaluated as 1434.176 kWh and corresponding EPBT was calculated as 4.21 years.
- Total CO₂ mitigation using ITDHSD for tomato drying in lifetime of 20 years was estimated 12.28 tonnes.
- Earned carbon credit by ITDHSD for tomato drying was evaluated as US \$364.
- Total initial capital and operating cost for ITDHSD system were computed as US \$245 and US \$563, respectively and the corresponding payback period for selling dried tomato flakes was estimated as 6 months.
- Dried tomato flakes obtained from ITDHSD were of good quality in terms of sensory analysis, rehydration ratio, shrinkage and hardness compared to open sun-dried tomato flakes.
- ITDHSD system has been found economical in terms of monetary value as well as in terms of carbon mitigation.

In next chapter, a novel sinusoidal corrugated solar collector has been designed, developed and its integration with domestic hybrid solar dryer has been examined using CFD simulations.

CHAPTER-V

COMPUTATIONAL FLUID DYNAMICS SIMULATION AND THERMAL PERFORMANCE EVALUATION OF INDIRECT TYPE DOMESTIC HYBRID SOLAR DRYER EMBEDDED WITH SINUSOIDAL CORRUGATED SO-LAR COLLECTOR

5.1. Introduction

Food preservation through drying is a critical technique that extends the storage of crops with low shelf life [29], [142]. Both conventional and solar drying methods are used, with conventional drying utilizing electricity that is converted into heat energy [69][143]. However, this conversion process is not efficient or economical as the electrical power generated primarily comes from non-renewable sources and results in the release of GHG into the environment [1], [3], [75], [82]. As a result, solar drying is favored over conventional drying. While many domestic users opt for the simple method of open sun drying, it is not effective and leaves the food vulnerable to spoilage from elements such as rain, animals, and fungus. Drying the food in a controlled environment resolves these issues [73].

A controlled environment for food drying can be achieved through the use of specialized equipment known as solar dryers [22], [120]. There are three main types of solar dryers: direct, indirect, and mixed mode. Both industrial and house-hold versions of these dryers have been created. The combination of a top-quality dried product and an efficient dryer is ideal for domestic users. Numerical design and simulation play crucial roles in verifying a design for researchers, avoiding the waste of time and resources on testing and building an inefficient and impractical design [62], [70].

Many researchers favour the use of CFD simulation to analyze different parameters within solar dryers. For example, Chavan et al. [55] carried out a CFD simulation of a solar grain dryer and tested different designs, optimizing the system and determining the overall performance. In the end, they proposed two different designs. Singh et al. [56] utilized CFD modeling to assess the thermal and dynamic performance of an indirect forced convection solar dryer at various mass flow rates, using the results of their experiments to validate the simulated data. Mellalou et al. [57] built a modified greenhouse dryer with an uneven span and used CFD modeling to understand the temperature distribution within the dryer, validating the simulation with the findings from their experiments. Jain et al. [62] analyzed a domestic direct multi-shelf solar dryer using ANSYS FLUENT software, evaluated the temperature distribution and pressure distribution of absorbed

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solar radiation. Demissie et al. [61] developed an indirect solar food dryer and performed simulations of the three-dimensional flow field and temperature distribution within the drying chamber. Sanghi et al. [64] created a CFD model to simulate the performance of drying in a solar corn dryer, visualizing temperature, humidity, and air velocity inside the dryer and validating the simulation results with experimental results. Sonthawi et al. [66] designed a solar biomass hybrid dryer and modeled it using ANSYS-FLUENT CFD simulation software, analyzing the distributions of temperature and airflow.

The prime focus of this research work is to investigate indirect domestic hybrid solar dryer embedded with sinusoidal corrugated thermal collector system. This system is developed to support agriculturists for process industry applications.

5.2. System Description

To improve the solar dryer system performance an Indirect domestic hybrid solar dryer (ITDHSD) with sinusoidal corrugation has been proposed. Figure 5.1(a) displayed cross-sectional view of ITDHSD system. Main components of ITDHSD system and their dimensions are displayed in Table 5.1.



Figure 5.1 (a) Cross-sectional view of designed indirect type domestic hybrid solar dryer (ITDHSD) system

As depicted in Figure 5.1(a), the solar collector will be operated in indirect forced mode, solar radiation will fall against the glass and then be transmitted and absorbed by copper absorber box by means of conduction, convection, and radiation heat transfer modes. The working fluid, which is ambient air, flows over the surface of the absorber box as it enters the solar collector from the inlet. Due to convection heat transfer, the surrounding air absorbs thermal energy from the absorber box and moves upward into the drying cabinet's inlet. Heated air contacts food crop and absorbs its moisture, then escapes through outlet with assistance of exhaust fan. This entire procedure proceeds until crop gets dry.

A fan is fixed at the outlet for which electric powers is provided using 20 W PV module. PV module was mounted over the top of drying cabinet. Drying cabinet consisted of three wiremesh trays which can be used to keep food during drying. ITDHSD had been attached with a novel sinusoidal corrugated thermal collector. Sinusoidal corrugated absorber box is displayed in Figure 5.1(b). The absorber box made from copper sheet and sinusoidal corrugation was provided over the width of the absorber using copper wire of diameter 1.5 mm.

Components	Dimensions (mm)
Solar collector	$1200\times 600\times 100$
Drying cabinet	$600 \times 600 \times 700$
Absorber box	$1000 \times 500 \times 60$
Wire mesh trays	500 × 500
Inlet	1200×40
Outlet	100

 Table 5.1. ITDHSD embedded with sinusoidal solar collector system's components and their dimensions

5.2.1. Solar collector's design

It is well known that adding artificial roughness characteristics to a solar air collector's absorber surface, often referred to as the heat transfer surface, can greatly increase the heat transfer coefficient between that surface and the air passing past it. The system's overall thermal efficiency is improved as a result of this modification. It's crucial to remember that this improvement also necessitates a greater amount of pumping force to move the air through the roughened duct.

It becomes necessary to carefully evaluate these roughness elements' features, such as their shape, size, and the subsequent flow pattern they produce, to achieve the optimum level of efficiency while reducing frictional losses. Consequently, a key parameter that considers both the thermal and hydraulic (friction-related) performance, referred to as the Thermo-hydraulic performance of the Solar Air Collector, must be employed as a means to ascertain the optimal roughness geometry for the system. Following parameters have been considered while designing the sinusoidal absorber for indirect domestic hybrid solar dryer:

• Diameter of circle of which arc is made of, can be calculated by the relation given below (Singh et al. 2014)

•
$$D = \frac{a}{\cos(90-\alpha)}$$
 (5.1)

• Chord length, a is calculated by the relation,

•
$$a = \frac{w}{2}$$
 (5.2)

• Relative roughness pitch is the ratio given by, (Kumar et al. 2016)

$$\bullet \quad \frac{p}{e} = 8 \tag{5.3}$$

• Radius of the of which arc is made is given by,

•
$$R = \frac{D}{2}$$
(5.4)

• Relative roughness width is given as, (Kumar et al. 2016)

$$\bullet \quad \frac{W}{w} = 3 \tag{5.5}$$

• Height of chord, sagitta (In geometry, the sagitta of a circular arc is the distance from the centre of the arc to the centre of its base), can be calculated as,

$$\circ \quad \text{Sagitta} = \left\{ R - \sqrt{R^2 - \left(\frac{a}{2}\right)^2} \right\}$$
(5.6)

Table 5.2 shows different design parameters and their respective value used for designing the sinusoidal solar collector for indirect domestic hybrid solar dryer. Figure 5.1(b) shows the solar collector design and design of a single sine wave in sinusoidal corrugated solar collector.



Figure 5.1(b). Details of sinusoidal corrugation on absorber mounted inside the solar collector Table 5.2. Design parameter for sinusoidal corrugated absorber of indirect domestic hybrid solar

dryer

S.No.	Design parameter	Value
1.	Diameter of circle, D	96.96 mm
2.	Chord length (a)	83.33 mm
3.	Relative roughness pitch (p/e)	8
4.	Arc angle $(\alpha/90^{\circ})$	60 [®]
5.	Radius of circle, R	48.48 mm
6.	W/w	3
7.	Pitch (p)	12 mm
8.	W (width of absorber plate)	500 mm
9.	w (width of complete cycle)	166.66 mm
10.	e (height of roughness)	1.5 mm
11.	Height of chord (sagitta)	23 mm

5.3. Methodology

The following methodology has been carried out to evaluate the performance of ITDHSD embedded with sinusoidal corrugated collector system. Flow chart showing the methodology has been displayed in Figure 5.2.



Figure 5.2. Flowchart for CFD Simulation [15]

5.3.1. Simulation approach

The simulation of ITDHSD embedded with sinusoidal corrugated collector was completed using the ANSYS FLUENT software. Different assumptions and boundary conditions were used for simulation, and outcome was computed by utilising ANSYS FLUENT to solve the governing equations.

5.3.1.1. Geometric model

The geometric model of ITDHSD was constructed using Ansys Workbench SpaceClaim in 3D. It was drawn according to dimensions of components mentioned in Table 5.1. Further meshing of designed model was performed in Ansys fluent meshing software. Obtained mesh elements were in the range of 5.1 million. Appropriate quality control factors such as skewness were taken into consideration for the mesh and grid independency test were performed for four different mesh configurations. Skewness for mesh on which final solution was performed was 0.42.

5.3.1.2. Assumptions

Assumptions made in the CFD simulation of ITDHSD embedded with sinusoidal corrugated collector are as follows:

- Problem was considered as three dimensional and steady state.
- The working fluid is assumed to be an ideal gas.
- The flow is assumed to be steady and incompressible.
- The geometry of the solar dryer is assumed to be symmetrical.
- Dryer walls were considered insulated and motionless.
- The solar dryer is assumed to be operating under no load conditions.

5.3.1.3. Boundary conditions

Boundary conditions for numerical simulation of ITDHSD embedded with sinusoidal corrugated thermal collector were as follows:

• Initial temperature of air (working fluid) was 300 K.

- All system parts were taken for meshing procedure to obtain good results from CFD simulations.
- Realizable k-ε model with scalable wall functions was considered to simulate effect of turbulent flow inside ITDHSD system.
- Solar load model was taken to calculate effects of solar insolation entering in the computational domain.

Design Parameter	Numeric Value	
Latitude and longitude	28.4506° N and 77.5842° E	
Date	21 st November	
Time zone	+ 5.5	
Density of air, ρ_a	1.164 kg/m ³	
Specific heat of air, C _{pa}	1007 J/kg-K	
Thermal conductivity of air, Ka	0.025 W/m-K	
Viscosity of air, µa	1.8724 e -05	
Absorber material	Copper	
Absorptivity of absorber surface, α_c	0.8	
Thickness, t _c	1 mm	
Density of copper, ρ_c	8978 kg/m ³	
Specific heat of copper, C _{pc}	381 J/kg-K	
Thermal conductivity of copper, K _c	387.6 W/m-K	
Wall material	Acrylic Sheet	
Thickness, t _{ac}	5 mm	
Density of Acrylic Sheet, ρ_{ac}	1190 kg/m ³	
Specific heat of Acrylic Sheet, C _{pac}	1470 J/kg-K	
Thermal conductivity of Acrylic Sheet,	$0.19 \text{ W/m}_{-}K$	
K _{ac}		
Glazing material	Glass sheet	
Thickness, t _{gs}	5 mm	
Density of Glass sheet, ρ_{gs}	2500 kg/m ³	
Specific heat of Glass sheet, C _{pgs}	750 J/kg-K	
Thermal conductivity of Glass sheet, K_{gs}	1.05W/m-K	

 Table 5.3. Various design parameters for CFD simulation of ITDHSD solar dryer system

5.3.1.4. Governing Equations

Numerical simulation of designed ITDHSD is necessary step, hence it is critical to choose the right equations that can be further solved with ANSYS-FLUENT. Any standard model must use CFD simulation to simulate several working fluid property parameters, including pressure, temperature, and velocity. The different conservation equations (Eqs. 5.7-5.10) governing the flow behaviour must be solved. These equations are as follows:

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho \mathbf{v}) = \mathbf{0}$$
 (5.7)

Momentum conservation equation:

$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla .(\rho \mathbf{v} \mathbf{v}) = -\nabla \mathbf{p} + \rho \mathbf{g} + \mathbf{F}$$
(5.8)

Energy Conservation equation:

$$\frac{\partial}{\partial t}(\rho E) + \nabla [v(\rho E + p)] = 0$$
(5.9)

Heat transfer radiation equation:

$$\frac{\mathrm{d}I(\mathbf{r},s)}{\mathrm{d}s} + (\mathbf{a} + \sigma_s)\mathbf{I}(\mathbf{r},s) = \mathbf{a}\mathbf{n}^2\frac{\sigma T^4}{\pi} + \frac{\sigma_s}{\pi}\int_0^{4\pi}\mathbf{I}(\mathbf{r},s)\boldsymbol{\varphi}(s,s')\mathbf{d}\Omega' \qquad 5.10$$

5.3.2. Thermal Performance Parameters

Thermal performance parameters were assessed using unload simulation results to evaluate the ITDHSD design and performance under active mode. This evaluation is necessary to determine a solar dryer's ability to utilize and convert the radiant solar insolation to thermal energy. Following thermal performance parameters were calculated for ITDHSD during active mode operation:

5.3.2.1. Coefficient of performance (COP)

It is the fraction of the difference in temperature between average drying temperature (T_{dc}) and ambient temperature (T_i) to the difference in temperature between solar collector's outlet (T_{sc}) and ambient. The expression to calculate COP is as follows [43], [62]:

$$COP = \frac{(T_{dc} - T_i)}{(T_{sc} - T_i)}$$
(5.11)

5.3.2.2. Heat utilization factor (HUF)

It is related to the decrease in temperature due to air cooling and increased temperature due to air heating. The expression to evaluate HUF is as follows [43], [108]:

$$HUF = \frac{(T_{sc} - T_{dc})}{(T_{sc} - T_i)}$$
(5.12)

5.3.2.3. Heat gain by air (Q_a)

The heat is absorbed by the air flowing through the collector. The heat absorbed can be calculated by measuring air temperature at the inlet and outlet of dryer. The expression for heat gain by air is as follows [31], [62]:

$$Q_a = \dot{m}c_{pa}(T_{do} - T_i) \tag{5.13}$$

5.3.2.4. Thermal efficiency $(\eta_{thermal})$

Thermal efficiency is defined as the ratio of thermal energy absorbed by air from solar collector to the solar energy input to the collector. It is expressed as [22], [31]:

$$\eta_{thermal} = \frac{Q_a}{I_g A_{sc}} \tag{5.14}$$

5.4. Result and discussion

5.4.1. Simulation results

The input design parameters for the CFD simulation of ITDHSD embedded with sinusoidal corrugated solar collector are mentioned in Table 5.3. The grid independence test was performed before final simulation to obtain results. As mentioned in Table 5.3, four different grids were tested and after simulation grid with 5.1 million elements was found suitable for simulation. Figure 5.4 shows meshed view of designed system.

S. No	Mesh Type	No. of ele-	Temperature
5. INU.		ments	(K)
1.	Tetrahedral/mixed	33,25,025	360
2.	Tetrahedral/mixed	45,41,250	340
3.	Tetrahedral/mixed	51,24,221	323.79
4.	Tetrahedral/mixed	57,24,481	324

Table 5.4. Grid Independence test



Figure 5.3. Meshed view of designed indirect type domestic hybrid solar dryer (ITDHSD) system

Mass flow rate for ITDHSD embedded with sinusoidal corrugated solar collector was optimised by simulating the system at 500 W/m² under unload conditions. Thermal behaviour of working fluid (air) was analysed at five different inlet air velocities i.e., 0.2 m/s (\dot{m} = 0.0067 kg/s), 0.4 m/s (\dot{m} = 0.0134 kg/s), 0.6 m/s (\dot{m} = 0.0201 kg/s), 0.8 m/s (\dot{m} = 0.0268 kg/s) and 1 m/s (\dot{m} = 0.0335 kg/s). Temperature contours generated at the mid-section of system have been displayed in Figure 5.4(a-e).





(b) v = 0.4 m/s (\dot{m} = 0.0134 kg/s)


(c) v = 0.6 m/s ($\dot{m}= 0.0201 \text{ kg/s}$)



(d) v = 0.8 m/s (\dot{m} = 0.0268 kg/s)



(e) v = 1 m/s ($\dot{m} = 0.0335 \text{ kg/s}$)

Figure 5.4 (a-e). Temperature distribution contour in ITDHSD embedded with sinusoidal corrugation at different mass flow rate (at solar insolation value of 500 W/m²)

These contours were studied, and results have been depicted in Figure 5.5. It was observed that at a low mass flow rate of 0.0067 kg/s, the air acquired a very high temperature of 398.8 K at the collector outlet and the average temperature of air inside the drying cabinet was 345.06 K. As the mass flow rate was increased to 0.0134 kg/s, 0.0201 kg/s, 0.0268 kg/s and 0.0335 kg/s, the temperature of the air at the collector outlet was observed as 357.6 K, 339.89 K, 328.69 K and 323.78 K, respectively, and their corresponding average air temperature in the drying cabinet was reported as 330.93 K, 323.79 K, 317.25 K and 314.58 K.



Figure 5.5. Temperature distribution in ITDHSD embedded with sinusoidal corrugation at different inlet air velocity at solar insolation value of 500 W/m²

The typical solar irradiation in tropical countries is in the range of 500 W/m² to 1000 W/m² and as the solar irradiation increases, the temperature of the collector surface and the air inside the collector and drying cabinet will rise. Most crop drying temperatures fall within the range of 318.15 K to 348.15 K [31], [33]. Therefore, low mass flow rates of air, i.e., 0.0067 kg/s and 0.0134 kg/s, were not considered according to the simulation results. Furthermore, the average air temperature inside the drying cabinet during higher mass flow rates of 0.0268 kg/s and 0.0335 kg/s was found to be less than the optimum temperature range needed for crop drying. So, these mass flow rates have also been excluded. Hence, the mass flow rate 0.0201 kg/s corresponding to an inlet air velocity of 0.6 m/s is suitable for drying crops inside ITDHSD embedded with a sinusoidal corrugated solar collector.

Furthermore, thermal behaviour of the ITDHSD embedded with a sinusoidal corrugated solar collector was depicted using CFD simulation at different solar irradiation values varied from 500 W/m² -1000 W/m². Temperature contours for the

ITDHSD system at the optimum mass flow rate of 0.0201 kg/s were displayed in Figure 5.6 (a-f).







(d) $I_d = 800 \text{ W/m}^2$





Thermal behaviour of the system under different solar irradiation values is displayed in Figure 5.7. It can be observed that while the solar irradiation increases, the temperature of air increases simultaneously. At 500 W/m², average dryer temperature was 323.79 K and it increased simultaneously as the solar irradiation rose to 600 W/m², 700 W/m², 800 W/m², 900 W/m² and 1000 W/m². This validates the design of ITDHSD drying system.



Figure 5.7. Temperature variation at inlet air velocity (v=0.6 m/s) in ITDHSD embedded with sinusoidal corrugation at different solar irradiation

ITDHSD system was simulated for 21st May at mass flow rate of 0.0201 kg/s from 09:00 to 17:00. Solar insolation as predicted by solar load model falls between 703 W/m² to 905 W/m². Ambient air temperature was taken as 305 K. The values for collector outlet temperature, average dryer temperature and drying outlet temperature throughout the day were evaluated as 340-350.6 K, 325-334 K and 319.5 to 328 K, respectively as depicted in Figure 5.8. The maximum value for solar insolation, collector outlet and average dryer temperature was 905 W/m², 305.6 K and 334 K, respectively at 12:00 PM.



Figure 5.8. Hourly variation of temperature and solar insolation at inlet air velocity (v=0.6 m/s) in ITDHSD embedded with sinusoidal corrugation simulated for 21st May 2023

Furthermore, theoretical performance parameters namely HUF, COP and thermal efficiency for ITDHSD embedded with sinusoidal corrugated solar collector were estimated as per simulation results using Eqs.s 5.11, 5.12, and 5.14. Figure 5.9 displayed hourly variation of thermal efficiency with solar insolation. It was observed that as solar insolation increases, thermal efficiency of system also increases, and it reached a maximum value of 71.3% at a corresponding value of 905 W/m² for solar insolation.



Figure 5.9. Hourly thermal efficiency and solar insolation at inlet air velocity (v=0.6 m/s) in ITDHSD embedded with sinusoidal corrugation simulated for 21st May 2023

Figure 5.10 shows hourly variation of HUF and COP. During the day, HUF and COP were in the range of 0.34-0.43 and 0.56-0.65, respectively. It is depicted in Figure 5.10 that as HUF increased during the day, COP of the dryer decreased correspondingly.



Figure 5.10. Hourly variation in heat utilisation factor (HUF) vs coefficient of performance (COP) at inlet air velocity (v=0.6 m/s) in ITDHSD embedded with sinusoidal corrugation simulated for 21st May 2023

5.4.2. Validation

Table 5.5 shows the comparison of present simulated ITDHSD system with other developed indirect type solar dryer. During summer season, developed indirect solar dryers [51], [144] accumulated the maximum dryer temperature and maximum collector outlet temperature in the range of 336-351 K and 348-354 K, respectively. Currently, simulated ITDHSD system embedded with sinusoidal corrugated solar collector accumulated maximum dryer temperature and maximum collector outlet temperature 334 K and 350.6 K, respectively at inlet air temperature of 305 K as predicted from simulation.

Furthermore, Sharma et al. [43] mentioned that HUF increases with time of the day and COP decreases with time of the day. Similar variation had been observed in Figure 5.10, as assessed from theoretical results obtained from CFD simulation of ITDHSD system. Moreover, Norton [33] suggested drying temperature of 310 K to 341 K for optimum drying of different crops as this is an adequate temperature to kill bacteria and inactive enzymes. Average dryer temperature of the present simulated system was in range of 325-334 K as observed in Figure 5.8. Therefore, all

the above statements validate the simulated ITDHSD embedded with sinusoidal solar collector system.

Literature	Drying system	Country	Season	Inlet tempera- ture (K)	Maximum dryer tem- perature (K)	Maximum collector outlet tempera- ture (K)
Bharadwaj et al. [145]	Indirect solar dryer without thermal energy storage	India	Winter	304	319.5	-
Lingayat et al. [51]	Indirect type solar dryer (ITSD)	India	Summer	311	351	354
Yaseen et al. [47]	Traditional indi- rect solar dryer	Iraq	Winter	298	322	335
Gilago et al. [144]	Passive indirect solar dryer with- out thermal en- ergy storage	India	Summer	314.7	336.5	348
Present simulated system	ITDHSD embed- ded with sinusoi- dal corrugated collector	India	Sum- mer	305	334	350.6

Table 5.5. Comparison of other developed solar dryer with present simulated drying system

5.5. Summary

Indirect type domestic hybrid solar dryer embedded with sinusoidal corrugated solar collector was proposed, designed, and simulated at Bennett University, Greater Noida (U.P.), India. Solar collector was proposed to consist of an absorber box to be built from copper sheet and have sinusoidal corrugation with the help of

wire of diameter 1.5 mm over it. CFD simulations were performed on the developed design, and it gave following conclusions:

- Simulations to optimize mass flow rate were performed at different mass flow rates ranging from 0.0067 kg/s to 0.0334 kg/s at 500 W/m² and mass flow rate of 0.0201 kg/s was found optimum for drying crops inside the dryer.
- Thermal behavior of designed solar dryer was performed at solar insolation ranging from 500 W/m² to 1000 W/m² to validate the proposed design and it was observed that average dryer temperature increased with rise in solar insolation.
- Drying system was simulated for 21st May (summer season) from 09:00 to 17:00 hours to assess thermal performance of the drying system. It was observed that maximum theoretical thermal efficiency of the dryer was 71.3%.
- Average dryer temperature and collector outlet temperature were in the range of 340-350.6 K and 325-334 K, respectively.
- The performance of drying system was duly compared with existing drying systems to validate the results obtained from CFD simulation.

In next chapter, conclusions of the present work have been discussed and future work recommendations will be presented.

CHAPTER-VI

CONCLUSIONS AND FUTURE RECOMMENDATIONS

6.1. Conclusions

ITDHSD system was designed, simulated, and fabricated at the rooftop of Delhi Technological University (DTU), Delhi (India). The experiment under active mode for unload condition and load conditions was successfully concluded from 15th – 30th November 2021. Further, thermal performance parameters of ITDHSD system were evaluated. Tomato crop was used for drying experimentation in ITDHSD system. The following conclusions have been drawn:

- Simulation results showed that maximum temperature was generated at the solar collector which was around 350 K which validates the design of the system.
- Thermal efficiency of the solar collector in the ITDHSD had a maximum value of 59% at 13:00 hours.
- Final moisture content of 9% (wb) in tomato flakes was achieved after 10 hours of drying in ITDHSD while in open sun drying 14% (wb) moisture content was achieved after 14 hours.
- The maximum drying rate was found to be 0.47 kg of water/hour.
- Overall drying efficiency of the ITDHSD system was 41.05% and hourly drying efficiency was in the range of 4.04-68.78%.
- Exergy efficiency of the ITDHSD system varied from 32.86% to 58.26% and overall exergy efficiency was 46%.
- Prakash and Kumar model was found to be the best fit for tomato drying in ITDHSD.
- Heat utilization factor and COP for ITDHSD were in the range of 0.59-0.84 and 0.16-0.44, respectively.
- Embodied energy in fabrication of ITDHSD system was evaluated as 1434.176 kWh and corresponding EPBT was calculated as 4.21 years.
- Total CO₂ mitigation using ITDHSD for tomato drying in lifetime of 20 years was estimated 12.28 tonnes.
- Earned carbon credit by ITDHSD for tomato drying was evaluated as US \$364.

From comparison with several existing solar dryers, the present system was found superior and had high thermal efficiency, drying efficiency and system will mitigate good amount of CO₂ during its operation. Present ITDHSD system is beneficial for

domestic users and small and medium scale industries and could provide better livelihood to the farmers.

6.2. Future Recommendations

Based on the current studies, following recommendations have been made:

- Experimental investigation of designed indirect type domestic hybrid solar dryer embedded with sinusoidal corrugated collector can be done under unload conditions.
- Furthermore, developed system can be tested in load conditions for drying fruits and vegetables.
- Phase change materials can be used in developed absorber box to enhance its performance and can be tested for drying food crops.

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Appendix- I

S.No.	Time		Ambient P	aramete	rs		Temperature measured at different points of Indirect type domestic hybrid solar											
	(hours:min)						dryer (in K)											
		I_{g}	I _d	R _{ha}	Ta	Vi	T ₁	T ₂	T ₃	T_4	T 5	T ₆	T ₇	T ₈	T 9	T ₁₀	T ₁₁	T ₁₂
		(W/m2)	(W/m2)	(%)	(K)	(m/s)												
1	09:00	452	52	53	293	0.21	295	296	303	307	309	311	307	300	299	299	301	302
2	10:00	498	87	51.2	295	0.1	298	307	308	313	315	313	311	303	301	301	302	303
3	11:00	545	98	49.2	297	0.12	301	311	313	307	319	315	313	303	302	302	303	303
4	12:00	576	120	44.4	298	0.3	302	312	315	318	319	317	316	305	303	303	304	304
5	13:00	623	111	42.5	300	0.29	304	318	321.3	325	323	319	319	306	305	304	306	306
6	14:00	680	108	40.1	299	0.34	306	319	325	326	324	319	318	306	305	304	305	306
7	15:00	590	105	42.0	298	0.12	303	315	320	322	321	317	315	304	302	301	302	303
8	16:00	457	85	48.1	296	0.23	299	302	311	317	312	311	309	301	300	300	301	303

Table : Observations noted during unload experimentation of indirect type domestic hybrid solar dryer on 16th November 2021

Appendix- II

S.No.	Time		Ambient P	Paramete	Temperature measured at different points of Indirect type domestic hybrid solar													
	(hours:min)				dryer (in K)													
		Ig	Id	Rha	Та	Vi	T1	T2	T3	T4	T5	T6	T7	T8	Т9	T10	T11	T12
		(W/m2)	(W/m2)	(%)	(K)	(m/s)												
1	09:00	432	70	52.7	294	0.1	296	297	305	309	311	312	309	302	301	301	302	303
2	10:00	510	97	50.3	296	0.17	299	308	310	315	318	315	313	304	303	303	304	305
3	11:00	535	110	48.2	297	0.16	302	310	313	318	320	317	315	305	304	304	305	305
4	12:00	565	115	46.4	297	0.29	304	312	315	321	321	318	317	306	304	304	306	307
5	13:00	644	123	41.9	299	0.31	305	317	323	328	326	321	321	308	307	306	307	308
6	14:00	660	112	39.7	299	0.37	307	318	326	327	323	320	319	306	305	304	306	307
7	15:00	585	105	44.2	298	0.4	304	314	320	322	318	319	315	303	302	302	304	306
8	16:00	424	80	50.2	298	0.3	301	301	312	317	312	311	309	301	300	300	301	303

Table : Observations noted during unload experimentation of indirect type domestic hybrid solar dryer on 17th November 2021

Appendix- III

Table : Observations noted during unload experimentation of indirect type domestic hybrid solar dryer on 18th November 2021

	Time		Ambient	Paramet	ers		Temperature measured at different points of Indirect type domestic hybrid solar dryer (in K)												
S.No.	(hours:min)	Ig (W/m ²)	I _d (W/m ²)	R _{ha} (%)	Ta (K)	Vi (m/s)	T ₁	T ₂	T 3	T4	T 5	T6	T 7	T 8	T9	T 10	T 11	T ₁₂	
1	09:00	432	70	52.7	294	0.1	296	297	305	309	311	312	309	302	301	301	302	303	
2	10:00	510	97	50.3	296	0.17	299	308	310	315	318	315	313	304	303	303	304	305	
3	11:00	535	110	48.2	297	0.16	302	310	313	318	320	317	315	305	304	304	305	305	
4	12:00	565	115	46.4	297	0.29	304	312	315	321	321	318	317	306	304	304	306	307	
5	13:00	644	123	41.9	299	0.31	305	317	323	328	326	321	321	308	307	306	307	308	
6	14:00	660	112	39.7	299	0.37	307	318	326	327	323	320	319	306	305	304	306	307	
7	15:00	585	105	44.2	298	0.4	304	314	320	322	318	319	315	303	302	302	304	306	
8	16:00	424	80	50.2	298	0.3	301	301	312	317	312	311	309	301	300	300	301	303	

Appendix- IV

		An	ıbient	parai	neters				Dat	a colle	cted a	t vario	ous plac	ces ins	ide the	e indir	ect do	mestic	hybri	d solar	dryer	
	S.No.	Time	Ig	Id	R _{ha}	Ta	$\mathbf{V}_{\mathbf{a}}$	Vi	R _{he}	Ve	T ₁	T ₂	T ₃	T ₄	T 5	T ₆	T ₇	T ₈	T 9	T ₁₀	T ₁₁	T ₁₂
	1	09:30	412	65	53.5	293	0.2	0.1	31	3.71	293	296	304	308	310	301	308	307	305	304	305	305
	2	10:30	490	92	51	295	0.3	0.3	26.2	3.95	295	307	309	314	317	304	315	313	311	310	309	308
DAY	3	11:30	545	100	47.4	296	0.35	0.4	22.3	4.25	296	311	314	320	320	307	317	316	315	314	313	312
1	4	12:30	600	115	44.2	297	0.36	0.2	18.5	4.2	299	314	319	325	323	310	320	318	317	316	314	313
	5	13:30	650	120	41	298	0.3	0.3	17.2	4.13	300	318	326	328	323	314	322	321	320	319	317	316
	6	14:30	625	110	44	298	0.48	0.5	19	3.5	299	315	323	323	320	309	320	319	318	317	315	314
	7	15:30	490	100	48.2	297	0.85	0.2	22.5	4.2	297	308	315	318	314	306	317	315	313	312	311	310
	8	16:30	404	80	51	296	0.52	0.3	28.2	4.02	296	300	311	316	311	300	314	313	312	311	309	308
	9	09:30	425	74	53.6	293	0.43	0.3	38.2	3.5	293	306	304	307	310	301	306	305	302	301	300	298
DAY	10	10:30	485	105	52	294	0.35	0.1	37.5	3.69	294	307	309	311	317	304	312	310	307	306	305	303
2	11	11:30	555	110	47.1	295	0.48	0.2	36	4.2	297	311	314	317	320	307	317	315	312	311	309	307
	12	12:30	610	115	48.2	297	0.36	0.3	35.2	3.85	299	314	319	321	323	310	321	320	317	316	314	312

Table: Observations recorded during tomato drying experimentation in indirect type domestic hybrid solar dryer on 21st and 22nd November 2021

Appendix- V

		Aml	oient p	param	eters			Data collected at various places inside the indirect domestic hybrid solar dryer														
	S.No.	Time	$\mathbf{I}_{\mathbf{g}}$	Id	R _{ha}	Ta	Va	Vi	Rhe	Ve	T ₁	T ₂	T ₃	T 4	T 5	T 6	T ₇	T ₈	Т9	T ₁₀	T ₁₁	T ₁₂
	1	09:30	442	75	52.2	295	0.1	0.2	29.9	3.86	295	298	306	310	312	303	310	309	306	307	307	306
	2	10:30	520	102	49.7	297	0.2	0.2	25.1	4.1	297	309	311	316	319	306	317	315	312	311	310	309
DAY	3	11:30	575	110	46.1	298	0.3	0.4	21.2	4.4	298	313	316	322	322	309	319	318	316	315	314	314
1	4	12:30	630	125	42.9	299	0.3	0.2	17.4	4.35	301	316	321	327	325	312	322	320	318	316	315	315
	5	13:30	680	130	39.7	300	0.2	0.4	16.1	4.28	302	320	328	330	325	316	324	323	321	319	318	317
	6	14:30	655	120	42.7	300	0.4	0.5	17.9	3.65	301	317	325	325	322	311	322	321	319	317	316	315
	7	15:30	520	110	46.9	299	0.8	0.3	21.4	4.35	299	310	317	320	316	308	319	317	314	313	312	309
	8	16:30	434	90	49.7	298	0.5	0.3	27.1	4.17	298	302	313	318	313	302	316	315	313	311	310	308
	9	09:30	455	84	52.3	295	0.4	0.4	37.1	3.65	295	308	306	309	312	303	308	307	303	302	300	299
DAY	10	10:30	515	115	50.7	296	0.3	0.1	36.4	3.84	296	309	311	313	319	306	314	312	308	307	305	304
2	11	11:30	585	120	45.8	297	0.4	0.3	34.9	4.35	299	313	316	319	322	309	319	317	313	311	309	307
	12	12:30	640	125	46.9	299	0.3	0.3	34.1	4	301	316	321	323	325	312	323	322	318	316	314	312

Table: Observations recorded during tomato drying experimentation in indirect type domestic hybrid solar dryer on 23rd and 24th November 2021
Appendix- VI

	Ambient parameters								Data collected at various places inside the indirect domestic hybrid solar dryer													
	S.No.	Time	Ig	$\mathbf{I}_{\mathbf{d}}$	R _{ha}	Ta	$\mathbf{V}_{\mathbf{a}}$	Vi	R _{he}	Ve	T ₁	T_2	T ₃	T 4	T 5	T ₆	T ₇	T ₈	T9	T ₁₀	T ₁₁	T ₁₂
	1	09:30	432	70	52.7	294	0.15	0.1	30.5	3.66	294	297	305	309	311	302	309	308	305	306	306	305
	2	10:30	510	97	50.3	296	0.25	0.2	26.5	3.95	296	308	310	315	318	305	316	314	311	310	309	308
DAY 1	3	11:30	565	115	46.4	297	0.41	0.3	21.3	4.63	297	312	315	321	321	308	318	317	315	314	313	313
	4	12:30	620	126	43.6	298	0.33	0.4	19	4.13	300	315	320	326	324	311	321	319	317	315	314	314
	5	13:30	670	117	40.5	299	0.29	0.3	18.5	4.09	301	319	327	329	324	315	323	322	320	318	317	316
	6	14:30	645	109	43.4	299	0.4	0.3	18	3.71	300	316	324	324	321	310	321	320	318	316	315	314
	7	15:30	510	88	49	298	0.96	0.6	21.4	4.56	298	309	316	319	315	307	318	316	313	312	311	308
	8	16:30	424	80	50.2	297	0.51	0.3	26.6	4.02	297	301	312	317	312	301	315	314	312	310	309	307
	9	09:30	445	74	52.5	294	0.15	0.1	40.1	3.66	294	307	305	308	311	302	307	306	302	301	299	298
DAY 2	10	10:30	505	102	51.1	295	0.25	0.2	38.2	3.95	295	308	310	312	318	305	313	311	307	306	304	303
	11	11:30	575	115	48.6	296	0.41	0.4	37.5	4.63	298	312	315	318	321	308	318	316	312	310	308	306
	12	12:30	630	118	47.1	298	0.33	0.4	37	4.13	300	315	320	322	324	311	322	321	317	315	313	311

Table: Observations recorded during tomato drying experimentation in indirect type domestic hybrid solar dryer on 25th and 26th November 2021

Appendix- VII

		Am	Data collected at various places inside the indirect solar dryer																			
	S.No.	Time	Ig	Id	Rha	Ta	Va	Vi	Rhe	Ve	T 1	T 2	T 3	T 4	T 5	T 6	T 7	T 8	Т9	T 10	T ₁₁	T ₁₂
	1	09:30	420	73	51.7	294	0.15	0.3	25	3.78	296	297	305	309	311	312	309	302	301	301	302	303
	2	10:30	510	100	49.3	296	0.25	0.2	23.5	3.8	299	308	310	315	318	315	313	304	303	303	304	305
DAY 1	3	11:30	535	118	47.2	297	0.41	0.3	15.8	4.75	302	310	313	318	320	317	315	305	304	304	305	305
	4	12:30	565	129	45.4	298	0.33	0.5	16	3.98	304	312	315	321	321	318	317	306	304	304	306	307
	5	13:30	644	120	40.9	299	0.29	0.2	13	4.21	305	317	323	328	326	321	321	308	307	306	307	308
	6	14:30	660	112	38.7	299	0.4	0.3	15	3.56	307	318	326	327	323	320	319	306	305	304	306	307
	7	15:30	585	91	43.2	298	0.96	1.1	15.9	4.68	304	314	320	322	318	319	315	303	302	302	304	312
	8	16:30	424	83	49.2	297	0.51	0.5	23.6	3.87	301	301	312	317	312	311	309	301	300	300	301	307
	9	09:30	425	77	55.1	294	0.15	0	34.6	3.78	294	307	305	308	311	302	307	306	302	301	299	298
DAY 2	10	10:30	485	105	52	295	0.25	0.4	35.2	3.8	295	308	310	312	318	305	313	311	307	306	304	303
	11	11:30	555	118	47.1	296	0.41	0.4	32	4.75	297	311	314	317	320	307	317	315	312	311	309	307
	12	12:30	610	121	46.5	298	0.33	0.2	34	3.98	299	314	319	321	323	310	321	320	317	316	314	312

Table: Observations recorded during tomato drying experimentation in indirect type domestic hybrid solar dryer on 27th and 28th November 2021

Appendix- VIII

Table: Observations recorded during tomato drying experimentation in indirect type domestic hybrid solar dryer on 29 th and 30 th November 2021

		Am	Data collected at various places inside the indirect solar dryer																			
	S.No.	Time	Ig	Id	Rha	Ta	Va	Vi	Rhe	Ve	T 1	T 2	T 3	T 4	T 5	T 6	T 7	T 8	Т9	T 10	T ₁₁	T ₁₂
	1	09:30	420	85	51.7	296	0.32	0.3	28	4.08	296	297	305	309	311	312	309	302	301	301	302	303
	2	10:30	510	118	49.3	298	0.25	0.2	26.5	2.3	299	308	310	315	318	315	313	304	303	303	304	305
DAY 1	3	11:30	535	129	47.2	299	0.31	0.3	18.8	2.65	302	310	313	318	320	317	315	305	304	304	305	305
	4	12:30	565	120	45.4	300	0.5	0.5	19	4.28	304	312	315	321	321	318	317	306	304	304	306	307
	5	13:30	644	112	40.9	301	0.29	0.3	16	2.71	305	317	323	328	326	321	321	308	307	306	307	308
	6	14:30	660	126	38.7	301	0.3	0.3	18	1.46	307	318	326	327	323	320	319	306	305	304	306	307
	7	15:30	585	117	43.2	300	1.13	1.1	18.9	4.98	304	314	320	322	318	319	315	303	302	302	304	306
	8	16:30	420	109	49.2	299	0.51	0.5	26.6	2.37	301	301	312	317	312	311	309	301	300	300	301	303
	9	09:30	425	88	55.1	296	0.05	0	37.6	1.68	296	297	305	309	311	312	309	302	301	301	302	303
DAY 2	10	10:30	515	80	52	297	0.42	0.4	38.2	4.1	299	308	310	315	318	315	313	304	303	303	304	305
	11	11:30	585	74	47.1	298	0.41	0.4	35	3.25	302	310	313	318	320	317	315	305	304	304	305	305
	12	12:30	640	102	46.5	300	0.23	0.2	37	1.88	304	312	315	321	321	318	317	306	304	304	306	307

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- M. Sharma, D. Atheaya and A. Kumar, "Performance Evaluation of an Indirect-Type Domestic Hybrid Solar Dryer for Tomato Drying: Thermal, Embodied, Economical, and Quality Analysis", Thermal Science and Engineering Progress, Vol. 42, 101882, 2023, <u>https://doi.org/10.1016/j.tsep.2023.101882</u>, (I.F. 4.8)
- M. Sharma, D. Atheaya and A. Kumar, "Exergy, drying kinetics and performance assessment of Solanum lycopersicum (tomatoes) drying in an indirect type domestic hybrid solar dryer (ITDHSD) system", Journal of Food Processing and Preservation, vol. 46, e16988, 2022, <u>https://doi.org/10.1111/jfpp.16988</u> (I.F. 2.609)
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