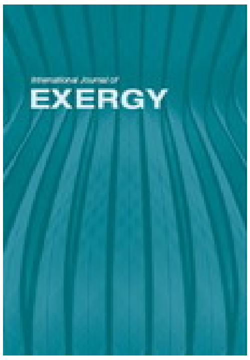


International Journal of Exergy

ISSN online: 1742-8300 - ISSN print: 1742-8297
https://www.inderscience.com/ijex

Experimental investigation and energy-exergy analysis of indirect liquid jaggery-making system based on parabolic dish concentrator

Vikrant Kumar, Chandrashekara M, Avadhesh Yadav

DOI: 10.1504/IJEX.2024.10062055

Article History:

Received:	18 July 2023
Last revised:	26 December 2023
Accepted:	31 December 2023
Published online:	01 February 2024

Experimental investigation and energy-exergy analysis of indirect liquid jaggery-making system based on parabolic dish concentrator

Vikrant Kumar*

School of Renewable Energy and Efficiency,
National Institute of Technology,
Kurukshetra, Haryana, 136119, India
Email: vikrantkamboj71@gmail.com
*Corresponding author

Chandrashekara M

Department of Mechanical Engineering,
National Institute of Technology,
Kurukshetra, Haryana, 136119, India
Email: chandru3@nitkkr.ac.in

Avadhesh Yadav

Solar Thermal Division,
National Institute of Solar Energy,
Gurugram, Haryana, 122003, India
Email: avadheshyadava@nise.res.in

Abstract: In this research, a novel indirect liquid jaggery-making system based on solar energy has been devised and assessed indoors in the climate of northern India. The thermic oil serving as the heat transfer fluid in the conical cavity receiver is heated using a parabolic dish concentrator. This accumulated intense heat is conveyed through connecting pipes to an indoor cooking pan. The system's performance was assessed over three consecutive days, processing 1 kg of sugarcane juice. Additionally, energy and exergy analyses were conducted, revealing a maximum energy efficiency of 11.08% and a maximum exergy efficiency of 2.31% for the system.

Keywords: parabolic dish concentrator; solar cooking; liquid jaggery; heat transfer fluid; HTF; energy efficiency; exergy efficiency.

Reference to this paper should be made as follows: Kumar, V., Chandrashekara M and Yadav, A. (2024) 'Experimental investigation and energy-exergy analysis of indirect liquid jaggery-making system based on parabolic dish concentrator', *Int. J. Exergy*, Vol. 43, No. 1, pp.59–80.

Biographical notes: Vikrant Kumar received his BTech in Mechanical Engineering from the Kurukshetra University, Kurukshetra, Haryana, India, and MTech from the National Institute of Technology, Kurukshetra, Haryana, India. He is pursuing his PhD from the National Institute of Technology, Kurukshetra, Haryana, India. He is presently working in the area of solar cooking based on a parabolic dish concentrator.

Chandrashekara M is working as an Assistant Professor in the Department of Mechanical Engineering, National Institute of Technology, Kurukshetra, Haryana, India. He received his PhD from the National Institute of Technology, Kurukshetra, Haryana, India. His area of interest is solar cooking, phase change materials, solar concentrator, and solar desalination. He has published more than 25 research papers in refereed journals.

Avadhesh Yadav is presently working as the Deputy Director General at the National Institute of Solar Energy, Gurugram, Haryana, India. He received his PhD from the National Institute of Technology, Kurukshetra, Haryana, India. His area of interest is desiccant air-conditioning systems, phase change materials, solar concentrators, solar cooking, and low and high-temperature solar energy applications. He has published more than 150 research papers in refereed journals. He has supervised ten doctoral theses and 50 MTech dissertations.

1 Introduction

Cooking accounts for around 36% of energy usage in a populous country like India. Using conventional biomass and fossil fuels as cooking fuels has several negative implications for the atmosphere and human health. Making jaggery is one of these processes. Evaporating water from sugarcane juice, which has an average water content of 85%–88%, requires significant energy (Kumar and Kumar, 2018). To generate concentrated goods, sugarcane juice is typically cooked in open containers in India using fossil fuels and bagasse. The traditional approach of simmering sugarcane liquid using conventional fuels causes environmental pollution, consumes much energy, and is not economical (Chaudhary and Yadav, 2021). Thus, another source is needed for such crucial concerns. Solar energy is one of the most tempting solutions to various problems, including climate change, high CO_2 emissions, fossil fuel depletion, rising power prices, and expanding global energy demand. Consequently, India has a shining future for solar cookers. Direct-type and indirect-type solar cookers are the two categories that may be used to classify solar cookers (Hosseinzadeh et al., 2021). Direct-type solar cookers, including focusing-type and non-focusing-type solar cookers, which employ sunlight directly for cooking purposes, have been extensively studied in previous research. In contrast, the cooking section and the solar collector are the two primary components of an indirect solar cooker. The cooking section can be positioned anywhere within the building, but the solar collector is outside. This kind involves transmitting high heat to the position of the cooking section via a thermal transmission medium heated by the solar collector. Indirect solar cookers thus provide the opportunity to cook indoors despite their more complicated structure and higher price than direct solar cookers (Harmim et al., 2013). Several investigations on the effectiveness of indirect solar cookers are available in the academic literature. Aramesh et al. (2019) compiled prior investigations on direct-type and indirect-type solar cookers. Stumpf et al. (2001) investigated and contrasted three indirect solar cookers through numerical and experimental analysis. The effectiveness of an indirect solar cooker made up of a vacuum tube solar collector was assessed analytically and empirically by Sharma et al. (2005). Singh et al. (2015) performed an experimental investigation to test the effectiveness of an indirect type solar cooker based on an ETSC using engine oil and water as the thermal transmission fluids.

Hosseinzadeh et al. (2021) experimented to determine the effects of utilising various heat transfer fluids (HTF) on the effectiveness of a novel indirect-type solar cooker. Dhiman and Sachdeva (2023) experimentally investigated the performance of an indirect solar cooking system based on a parabolic dish concentrator for indoor cooking. Additionally, numerous researchers have discussed different methods and techniques for effectively making jaggery. Tiwari et al. (2003) performed an indoor experiment to investigate mass and heat exchange in natural convection heating for jaggery production under open and closed circumstances. Shanmugan et al. (2014) manufactured and evaluated the thermodynamic effectiveness of a single-basin solar still for the concentration of palm tree juice in the jaggery-making process with and without an acrylic mirror booster. Using fuzzy logic in MATLAB, Jakkamputi and Mandapati (2016) suggested that using solar energy in preheating sugarcane juice and drying bagasse conserves heat energy and bagasse during jaggery manufacturing. Using computational fluid dynamics (CFD) analysis, La Madrid et al. (2016) investigated and assessed the thermal characteristics of the flue gases in the open-type heat exchanger used in the jaggery-making process. Khattak et al. (2018) introduced the exergy analysis technique for jaggery production. Marie et al. (2020) created a system for manufacturing jaggery that combines a freeze concentrator and solar thermal collector to pre-treatment sugarcane juice with standard bagasse-based jaggery-making equipment.

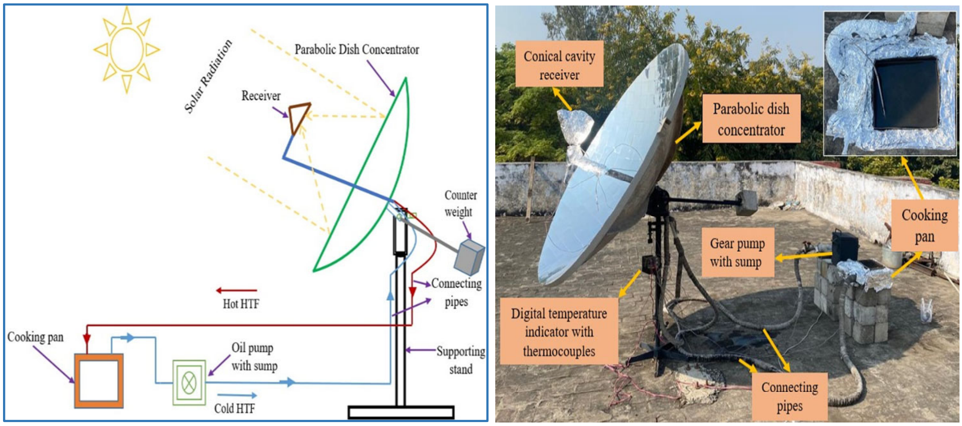
Numerous studies on the diverse types of solar cooking have been performed, as demonstrated by the literature reviewed. Most of the research on indirect solar cookers is focused on boiling cooking food. Research concerning jaggery production through indirect solar cookers is rarely seen in the literature. Furthermore, significantly less research has been conducted on the indirect making of liquid jaggery based on solar parabolic dish concentrators (PDC). In this research, an empirical evaluation of the performance of a novel indirect solar liquid jaggery-making system (SLJMS) based on PDC is conducted. In addition, a practical assessment of the energy and exergy efficiency of the indirect SLJMS has been undertaken. The novelty of this study is that it uses a high-temperature HTF at atmospheric pressure to heat the sugarcane juice in a cooking pan indoors.

2 Materials and methods

2.1 Experimental apparatus

Figure 1 depicts a schematic diagram and a photograph of the experimental apparatus that produces liquid jaggery. This system includes a solar PDC, a copper-made conical cavity receiver (CCR), a cooking pan, a sump or reservoir, a HTF, a rotary gear pump, and connecting pipelines. This experimental arrangement is located in the National Institute of Technology, Kurukshetra, India, at 29°58’ North and 76°53’ East latitude and longitude.

Figure 1 Schematic diagram and photographic view of the indirect jaggery-making experimental arrangement (see online version for colours)



2.1.1 Solar parabolic dish concentrator

In the experiment, a point-focus PDC concentrates solar energy on the receiver or focus. This concentrated radiation expedites the attainment of a high temperature. It comprises a parabolic-form primary reflector, a dual-axis manual tracking arrangement, a support stand, and a structure for keeping the absorber. Initially, PDC is created utilising a set of design calculations for jaggery production, and then a precise mould is manufactured. This particular mould is used to generate an accurate fibreglass casting. After curing, the dish construction is ready for installation. A solar-grade anodised metal sheet of 92% reflectivity was used on the concave side as a reflector. The PDC is monitored using a dual-axis tracking system to enhance energy utilisation. Table 1 shows the parameters specified for the PDC.

2.1.2 Conical cavity receiver

The CCR captures the concentrated heat. It has been formed by bending a copper tube with a 0.006 m diameter into a conical shape. To absorb solar radiation, the bottom frustum side fronts the PDC. A blackboard paint containing graphite powder is applied to the copper tube for optimal solar radiation absorption. Glass wool insulation 0.025 m thick was used on the CCR's top and sides to reduce heat loss. Figures 2(a) and 2(b) depicts the pictorial view and schematic layout of the CCR. The HTF within the CCR is circulated using a rotary gear pump. The discharge of the rotary gear pump is connected to the lower part of the CCR, while the upper portion of the CCR is linked to the sump's suction via connection pipelines.

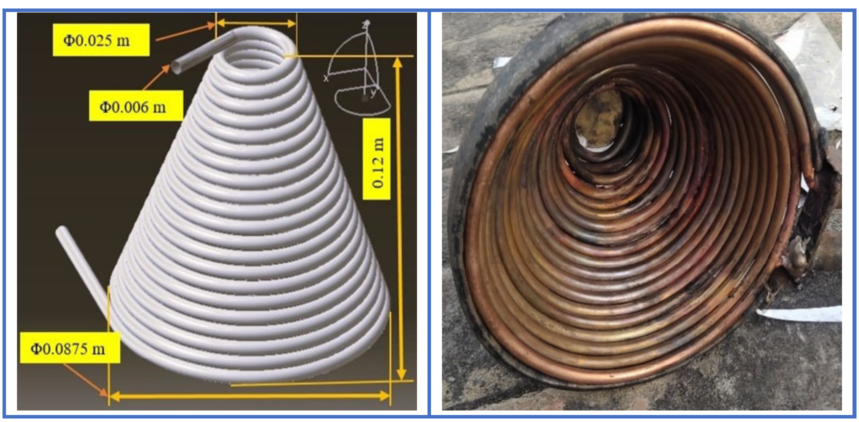
2.1.3 Cooking pan

The cooking pan is an essential component of the current experimental configuration. There are two parts to the cooking pan: a top part and a bottom one. A copper plate measuring 0.2 × 0.2 × 0.05 m comprises the top section; while an iron sheet measuring 0.2 × 0.2 × 0.035 m forms the bottom portion. Brazing is used to link them together. To enhance the surface area of the heating pan, rectangular baffles are welded to the lower part.

Table 1 Detailed geometrical specifications for solar PDC

Sr. no.	*Parameters used*	*Value*
1	Dia. of the parabola dish (D)	1.828 m
2	Depth of focus (h)	0.358 m
3	Length of focus (f)	0.583 m
4	Surface area (A_S)	2.993 m^2
5	Aperture area (A_a)	2.626 m^2
6	Rim angle (ϕ_r)	76.14°
7	Area of the receiver	0.0240 m^2
8	Concentration ratio	109

Figure 2 (a) Schematic view and (b) Photographic view of CCR (see online version for colours)



(a) (b)

With the aid of connecting pipes, the outlet of the CCR is linked to the cooking pot's inlet, and the outlet of the cooking pot is attached to the inlet of the sump. The cooking pot is encased in a timber frame made from plyboard sheets with a 0.02 m thickness. As insulation, a glass fibre coating with a thickness of 0.0254 m is inserted between the cooking pot and timber frame.

2.1.4 Connecting pipes

This experimental arrangement used flexible SS 304 stainless steel pipes of 0.015 m diameter to connect the CCR to the cooking pan, reservoir, and gear pump. In a closed circuit, the HTF circulates via these pipelines from the gear pump to the CCR. The above pipelines have been sufficiently covered to minimise heat loss to the environment via convection. The piping systems are attached with hexagonal fasteners pressed into the pipe ends to prevent leakage between pipelines and other components. These connecting pipelines can resist temperatures ranging from –20°C to 400°C.

2.1.5 Heat transfer fluid

Due to its chemical stability and safety, HPCL Hytherm-600 oil has been utilised as HTF to transmit energy from the CCR to the heating vessel. This particular HTF is capable of operating at temperatures as high as 320°C. The liquid's chemical and thermal characteristics are suitable for the current application.

2.1.6 Oil sump

Oil is stored in a mild steel tank that measures 0.12 × 0.12 × 0.16 m, known as the sump or reservoir. It conveys the HTF from the absorber end to the rotary gear pump for recirculation. To avert heat loss, the exterior surface of the oil reservoir is adequately insulated using thick glass fibre. As the HTF is heated and expands during heating, it also serves as an expansion reservoir to stop the fluid overflow. Additionally, the expansion reservoir prevents any pressure build-up in the system.

2.1.7 Gear pump

The motor gear pump is needed to pump a thick fluid at a high temperature throughout the system. The HTF has been pumped throughout the system using a magnetic-driven gear pump. Its purpose is to maintain a constant rate of the HTF flow to the CCR, irrespective of the length of the connecting pipelines. The HTF's flow rate is regulated using an elevated temperatures gate valve. The gear pump's discharge rate has been set to 1 L/min (litre per minute).

Table 2 Descriptions of measuring apparatuses

S. no.	*Measuring apparatus*	*Variables measured*	*Model no.*	*Accuracy*	*Range*
1	K-type temperature sensor	Temperature	COUNTRON	± 0.1 °C	0 to 1200 °C
2	Anemometer	Wind velocity	GILL INSTRUMENTS-WINDSONIC 75	± 0.24 m/s	0 to 75 m/s
3	Pyrheliometer	Direct normal irradiation	MIDDLETON SOLAR-DN 5	± 0.1 (W/m^2)	0 to 4000 (W/m^2)
4	Electronic weighing machine	Weight (sugarcane juice and liquid jaggery)	ATOM, SF-400A	± 0.1 g	0 to 10 kg
5	data logger	Data-acquisition system	SIAP+MICROS – DA 15K	-	-

2.2 Measuring devices and instruments

During examinations, the following accompanying limits are recorded:

- juice temperature
- wind speed
- HTF temperature
- solar direct normal irradiation (DNI)
- focus temperature
- ambient temperature.

The following instruments, detailed in Table 2, estimate these parameters.

2.3 Uncertainty analysis

The discrepancy between a parameter's estimated value and its actual value is known as an experimental error. An error could be unplanned or systematic. The uncertainty study allows the determination of errors in measured quantities. The uncertainties may result from various sources, including measurement devices and procedures, calibration mistakes, operator incompetence, experimental conditions, and environmental variables like temperature and wind speed. The uncertainty analysis was determined using the root mean square approach, and the following relationship can be employed to describe such examination (Kamboj et al., 2021):

$$v_Z = \left[\left(\frac{\partial Z}{\partial p_1} v_1\right)^2 + \left(\frac{\partial Z}{\partial p_2} v_2\right)^2 + \cdots + \left(\frac{\partial Z}{\partial p_n} v_n\right)^2\right]^{1/2} \tag{1}$$

where v_1, v_2, … v_n represents the uncertainties of the independent variables, v_Z represents the consequent uncertainty of the findings, and Z is the function of independent variables $p_1, p_2, \ldots p_n$.

The uncertainty in the overall energy efficiency analysis of indirect solar cooker is given by:

$$\begin{aligned}\partial\eta_{Ene} = \Bigg[&\left(\frac{\delta\eta_{Ene}}{\delta m_w}\right)^2 (\delta m_w)^2 + \left(\frac{\delta\eta_{Ene}}{\delta T_f}\right)^2 (\delta T_f)^2 + \left(\frac{\delta\eta_{Ene}}{\delta T_i}\right)^2 (\delta T_i)^2 \\ &+ \left(\frac{\delta\eta_{Ene}}{\delta m_{wv}}\right)^2 (\delta m_{wv})^2 + \left(\frac{\delta\eta_{Ene}}{\delta m_{l,Jag}}\right)^2 (\delta m_{l,Jag})^2 + \left(\frac{\delta\eta_{Ene}}{\delta T_s}\right)^2 (\delta T_s)^2 \\ &+ \left(\frac{\delta\eta_{Ene}}{\delta I_{DNI}}\right)^2 (\delta I_{DNI})^2 + \left(\frac{\delta\eta_{Ene}}{\delta t}\right)^2 (\delta t)^2 \Bigg]^{\frac{1}{2}}\end{aligned} \tag{2}$$

The uncertainty in the overall exergy efficiency analysis of indirect solar cooker is given by:

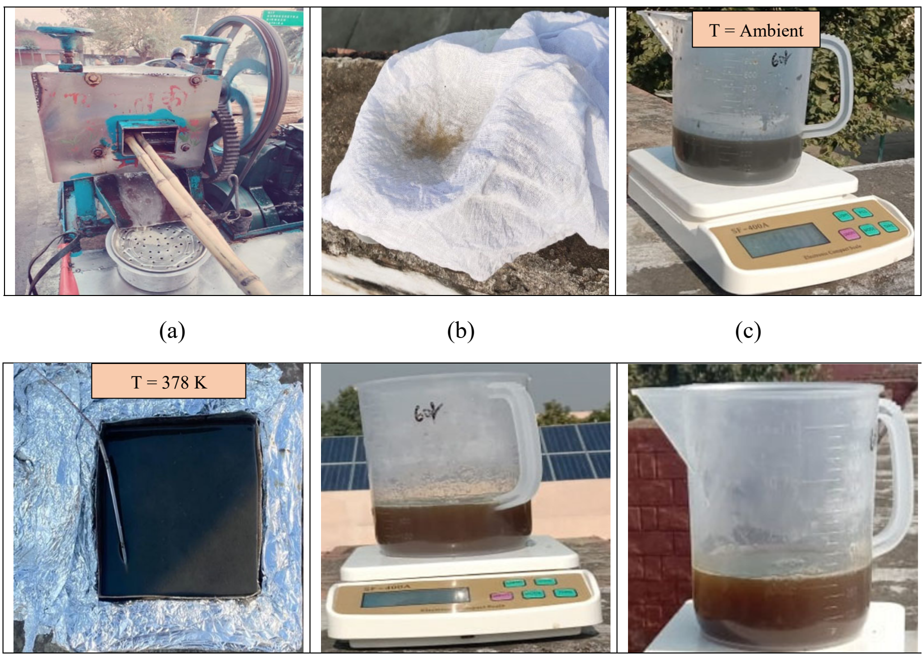
$$\partial\eta_{Ene} = \left[\left(\frac{\delta\eta_{Exe}}{\delta m_w} \right)^2 (\delta m_w)^2 + \left(\frac{\delta\eta_{Exe}}{\delta T_f} \right)^2 (\delta T_f)^2 + \left(\frac{\delta\eta_{Exe}}{\delta T_i} \right)^2 (\delta T_i)^2 + \left(\frac{\delta\eta_{Exe}}{\delta m_{wv}} \right)^2 (\delta m_{wv})^2 + \left(\frac{\delta\eta_{Exe}}{\delta m_{l,Jag}} \right)^2 (\delta m_{l,Jag})^2 + \left(\frac{\delta\eta_{Exe}}{\delta T_s} \right)^2 (\delta T_s)^2 + \left(\frac{\delta\eta_{Exe}}{\delta I_{DNI}} \right)^2 (\delta I_{DNI})^2 + \left(\frac{\delta\eta_{Exe}}{\delta t} \right)^2 (\delta t)^2 + \left(\frac{\delta\eta_{Exe}}{\delta T_{at}} \right)^2 (\delta T_{at})^2 \right]^{\frac{1}{2}} \quad (3)$$

The energy and exergy efficiency analysis uncertainty has been determined as 4.5% and 6.8% by considering equations (2) and (3), respectively.

2.4 System operation

A visual representation of the processes in the manufacturing of liquid jaggery is shown in Figure 3. The initial phase in jaggery production is to harvest sugarcane from the fields and crush it to extract the sugarcane juice in a crusher after weighing, as shown in Figure 3(a). The juice from the crushed sugarcane is then placed in a settling vessel and allowed to sit for a while to separate the heavier contaminants. The liquid from the settling container is again filtered through the thin cotton cloth to remove other foreign particles, as shown in Figure 3(b). This filtered juice is utilised in the study for jaggery production after being weighed, as depicted in Figure 3(c). The PDC works on the principle of focusing the sun's rays to the point of focus. A curved mirror plane collects sun rays and focuses these radiations at its focal point. The PDC's cover was removed, exposing the concentrator to the sun, which caused the PDC to begin focusing solar radiation on the CCR. Then, the motor of the rotary gear pump was started, and HTF began to circulate with a constant volumetric flow rate of 1 litre/min throughout the entire system. The discharge rate is determined throughout the experiments using a timer and a beaker. The temperature of the HTF increased due to the heat accumulation in the receiver tubes. This hot HTF flows through connected pipes to the cooking pan, where the filtered juice is heated, as shown in Figure 3(d). The sugarcane juice in the pot absorbs the high heat from the HTF by conduction and convection, and the low-temperature HTF is then returned to the CCR for recirculation. As a consequence, the cooking pot receives energy from the receiver continuously. The juice then begins heating in the cooking pan to evaporate the water. The fluid's strong thermal conductivity causes a quick increase in temperature. A steel strainer is used to manually remove the scum that developed during the sensible heating of the sugarcane juice. At around 95°C, the liquid produces vapour as it is heated continuously. The water contained in the cane juice begins to boil at 100°C due to continued heating, which causes the water to turn into steam. The quantity of heat delivered during this phase is regarded as the latent heat of vaporisation necessary for the conversion of water to steam. After this step, the sugarcane liquid will contain a high solids concentration due to completely removing water. In the final phase of liquid jaggery production, heat is used to raise the temperature of the sugarcane fluid from its simmering point to its striking point (105°C). The striking point temperature is the temperature at which sugarcane juice transforms into a semi-solid substance that glides on the pan's surface rather than adhering to it. After that, the semi-solid concentrated sugarcane juice is extracted from the cooking pan and allowed to cool to room temperature to create the liquid jaggery, as shown in Figures 3(e) and 3(f). As the solar intensity rises, the juice's temperature also increases. To prevent cosine losses, the PDC is tracked every five minutes regularly towards the sun. This procedure is repeated to prepare another batch of liquid jaggery. Sugarcane juice temperature (T_{juice}), CCR inlet temperature (T_{ci}), CCR outlet temperature (T_{co}), focus temperature (T_{focus}), pan inlet temperature (T_{pi}), pan outlet temperature (T_{po}), ambient temperature (T_{at}), wind velocity, and direct normal irradiance (DNI) are tracked and measured every five minutes.

Figure 3 (a) Juice collection from freshly crushed raw sugarcane, (b) Removing foreign substances from the juice by cotton cloth filtering, (c) A measurement of sugarcane juice, (d) Boiling of filtered juice in the heating process, (e) A measurement of hot liquid jaggery, (f) Final ready liquid jaggery (see online version for colours)



(a) (b) (c)

(d) (e) (f)

3 Analysis of experimental data

This section presents the energy and exergy analyses conducted to evaluate the efficacy of the indirect solar cooker's two primary components, the cooking pan and PDC. Furthermore, this study investigates the efficacy of the indirect SLJMS through an analysis of both energy and exergy. This research has been simplified by taking into account the following assumptions:

- The whole system is considered to be in steady state.
- Heat loss through the piping, valves and fitting is not considered.

- Pressure loses in the pipelines are neglected.

3.1 Parabolic dish concentrator

By considering the solar PDC is a control volume, the instantaneous energy efficiency (η_{PDC}) of the solar collector is obtained as follows (Kumar et al., 2023):

$$\eta_{PDC} = \frac{\dot{m}_f \times C_f \times (T_{r,out} - T_{r,in})}{A_{Aa} \times I_{DNI}} \tag{4}$$

In the above equation, I_{DNI} stands for the direct normal irradiation (W/m^2), and A_{Aa} denotes the attainable aperture area of solar PDC (m^2). Whereas $\dot{m}_f$ represents the mass flow rate of HTF. In addition, c_f is the specific heat capacity of the HTF. Moreover, $T_{r,in}$ and $T_{r,out}$ refer to the temperature of the HTF at the inlet and outlet of the receiver, respectively.

The instantaneous exergy efficiency of the solar collector ($\dot{E}x_{PDC}$) is calculated by the following equation:

$$\dot{E}x_{PDC} = \frac{m_f \times C_f \times \left[(T_{r,out} - T_{r,in}) - T_{at} \times \ln\left(\frac{T_{r,out}}{T_{r,in}}\right) \right]}{\left[1 + \frac{1}{3}\left(\frac{T_{at}}{T_{Sun}}\right)^4 - \frac{4}{3}\left(\frac{T_{at}}{T_{sun}}\right) \right] A_{Aa} \times I_{DNI}} \tag{5}$$

In the above equation: T_{at} (ambient temperature in K) and T_{Sun} (surface temperature of the Sun, 5,762 K).

3.2 Cooking pan

The input thermal power that the HTF provides is obtained by considering the cooking pan as a control volume. The average thermal power output of the cooking pan is obtained by calculating the average thermal energy absorbed by sugarcane juice during heating in a cooking pan. The average energy efficiency of the cooking pan (η_{cp}) is calculated by the given equation:

$$\eta_{cp} = \frac{\dfrac{\left[m_w \times C_{p,w} \times (T_f - T_i)\right] + \left[m_{wv} \times h_{fg}\right] + \left[m_{l,Jag} \times C_{pL,Jag} \times (T_s - T_i)\right]}{\Delta t}}{\dot{m}_f \times C_f \times (T_{c,in} - T_{c,out})} \tag{6}$$

The given equation involves several variables: mw (mass of water in kg), $C_{p,w}$ (specific heat of water, 4.187 kJ/kg.K), T_f and T_i (boiling temperature and initial temperature of water in the time interval in K), m_{wv} (mass of evaporated water in kg), and h_{fg} (latent heat of evaporation, 2,260 kJ/kg). During $m_{l,Jag}$ is the mass of liquid jaggery (kg), $C_{pL,Jag}$ is the specific heat of liquid jaggery (kJ/kg.K), and T_s is the striking point of liquid jaggery (378 K). Whereas, $T_{c,in}$ and $T_{c,out}$ are the temperature of the HTF at the inlet and outlet of the cooking pan in order.

Appendix A provides an exhaustive computation for determining $C_{pL,Jag}$ (Hugot, 1986).

The average exergy efficiency of the cooking unit (Ex_{cp}) during the time interval is obtained as follows:

$$Ex_{cp} = \frac{\dfrac{m_w \times C_{p,w} \times \left[\left(T_f - T_i\right) - T_{at} \times \ln\left(\dfrac{T_f}{T_i}\right) \right] + \left[m_{wv} \times h_{fg} \times \left(1 - \dfrac{T_{at}}{T_f}\right) \right] + m_{l,Jag} \times C_{pL,Jag} \times \left[\left(T_s - T_i\right) - T_{at} \times \ln\left(\dfrac{T_s}{T_i}\right) \right]}{\Delta t}}{\dot{m}_f \times C_f \times \left[\left(T_{c,In} - T_{c,Out}\right) - T_{at} \times \ln\left(\dfrac{T_{c,In}}{T_{c,Out}}\right) \right]} \quad (7)$$

3.3 *The overall performance of indirect solar cooker*

The indirect solar cooker's overall energy efficiency depends on the cooking unit's output thermal power and input solar power. It should be noted that in order to calculate the cooker efficiency, the consumed pumping power is subtracted from the output thermal power of the solar cooker. Thus, the overall energy efficiency of the indirect solar cooker is calculated using the following equation:

$$\eta_{Ov} = \frac{\dot{E}_{cp,Out} - \dot{E}_{pump}}{\dot{E}_{PDC,In,avg}} \quad (8)$$

In the above equation, $E_{PDC,In,avg}$ is the average rate of the input solar energy over the time interval. Consequently, the overall exergy efficiency of the indirect solar cooker is expressed as:

$$Ex_{Ov} = \frac{\dot{E}x_{cp,Out} - \dot{E}x_{pump}}{\dot{E}x_{PDC,In,avg}} \quad (9)$$

In which $Ex_{PDC,In,avg}$ refers to the average exergy rate of the input solar energy during the time interval. For the steady-state flow process during a finite time interval, the overall exergy balance of the solar cooker can be written as follows:

$$Ex_{In} = Ex_{Out} + Ex_{loss} + Irreversibility \quad (10)$$

The irreversibility of the solar cooker is due to the performance of the cooker dish and type of reflective material. These factors lead to heat loss due to improper concentration of the sunrays at the common focal point. The higher temperature difference between the heating load and surrounding air, the lower the exergy loss coefficient.

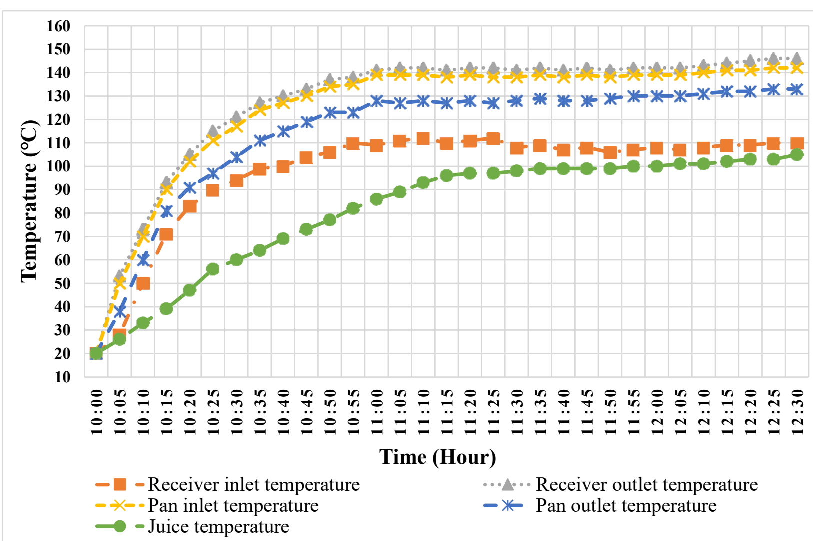
4 Experimental results and discussion

In November 2022, tests of a novel indirect heating system for producing liquid jaggery using a solar parabolic dish concentrator were conducted on days with clear skies. The ambient temperature of the local area ranged from 20°C to 25°C. The system is tested with 1 kg of sugarcane juice load for three consecutive days to check its performance. The experiments were conducted with an identical mass flow rate and around similar weather circumstances. For all experiments, the time-dependent variation graphs of ambient temperature, focus temperature, wind speed, and DNI are presented in Appendix B.

4.1 Test 1: with 1 kg of sugarcane juice on 23/11/2022

At 10:00 h, the procedure was initiated by circulating the HTF into the CCR with a rotary gear pump and adding 1 kg of sugarcane juice to a cooking pan. Figure 4 shows the time-dependent variations of T_{pi}, T_{po}, T_{ci}, T_{co}, and T_{juice} during the heating of sugarcane juice. The cooking pan cannot soak up all the CCR's output thermal energy in an indirect heating system. As a result, during the testing time, the HTF temperature at the CCR's input and output rises. A rising temperature trend throughout the system results from rising solar radiation. It took 20 min to raise the HTF temperature to 100°C. The maximum values of T_{co} and T_{ci} were 146°C and 110°C, respectively, at 12:25 h. The maximum values of T_{pi} and T_{po} were 142°C and 133°C, respectively, at 12:25 h. After 70 minutes of continuous heating, sugarcane juice reached 93°C, and the bubble-shaped scum was removed from the top surface. At 11:55 h, sugarcane juice reached the boiling temperature of 100°C. After boiling, steam began to form, and vapours emanated through the cooking pan's top. Subsequently, after 35 min of heating, the liquid started to thicken as the water dissipated, and it was further heated to its striking point. At 12:30 h, 0.225 kg of concentrated liquid syrup at 105°C is retrieved from the cooking pan after a large quantity of water has evaporated. It has been observed that the T_{focus} varies as the wind speed increases. In this instance, the whole process of making liquid jaggery took 150 min.

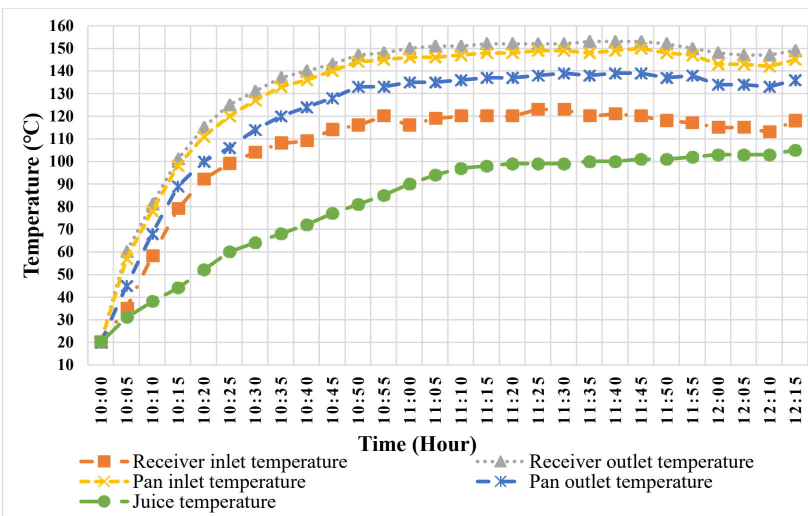
Figure 4 Time-dependent variations of T_{ci}, T_{co}, T_{pi}, T_{po}, and T_{juice} during the heating of 1 kg of sugarcane juice on 23/11/2022 (see online version for colours)



4.2 Test 2: with 1 kg of sugarcane juice on 24/11/2022

The next day, the current setup produced the liquid jaggery by heating 1 kg of sugarcane juice in the cooking pan. The value of solar DNI was increasing compared to the previous test. An abrupt decrease in solar DNI was observed at 11:55 h and 12:05 h, owing to clouds in the sky. Figure 5 shows the time-dependent variations of T_{ci}, T_{co}, T_{pi}, T_{po}, and T_{juice} during the heating of sugarcane juice. At various periods, the growth rate of the Tco was distinct. Since the HTF was repeatedly pumped between the CCR and the sump for the closed-loop experiment, the T_{ci} rose throughout the test. It took 15 minutes for the HTF temperature to reach 100°C. The maximum values of T_{co} and T_{ci} were 153°C and 120°C, respectively, at 11:35 h. The maximum values of T_{pi} and T_{po} were 150°C and 139°C, respectively, at 11:45 h. Scum was removed from the top after the liquid reached 94°C, which took about 65 minutes. The clear liquid began to simmer at 11:35 h after 95 minutes of constant heating. It is further heated until its striking point temperature, 105°C, arrives at 12:15 h. At 11:40 h, the highest T_{focus} attained was 685°C with a solar radiation of 923 W/m^2. In this instance, making liquid jaggery took 135 min., and 0.212 kg of liquid jaggery was produced.

Figure 5 Time-dependent variations of T_{ci}, T_{co}, T_{pi}, T_{po}, and T_{juice} during the heating of 1 kg of sugarcane juice on 24/11/2022 (see online version for colours)



4.3 Test 3: with 1 kg of sugarcane juice on 25/11/2022

Using the same experimental setup, 1 kg of sugarcane was poured at 10:00 h into the cooking pan to produce liquid jaggery. Due to the thermal energy accumulated over time, the HTF temperature grew along with the solar DNI. Figure 6 shows the time-dependent variations of T_{ci}, T_{co}, T_{pi}, T_{po}, and T_{juice} during the heating of sugarcane juice. The growth of the T_{ci}, T_{co}, T_{pi}, T_{po}, and T_{juice} depends on the solar DNI as it changes over time. During the initial 15 minutes of the experiment, the temperature of the HTF rose to 100°C. At 12:25 h, the maximum values of the T_{co} and T_{ci} were 118°C and 116°C, respectively. The maximum values of T_{pi} and T_{po} were 145°C and 136°C, respectively, at 12:25 h. At 11:10

h, the scum rose to the top of the cooking pan at 94°C and was removed. After 105 minutes of continuous heating, the clear liquid started to boil at 11:45 h. It is further heated until its striking point temperature, 105°C, arrives at 12:25 h. At 12:25 h, the highest T_{focus} attained was 685°C with a solar radiation of 893 W/m^2. In this instance, liquid jaggery took 145 min., and 0.220 kg was produced.

Figure 6 Time-dependent variations of T_{ci}, T_{co}, T_{pi}, T_{po}, and T_{juice} during the heating of 1 kg of sugarcane juice on 25/11/2022 (see online version for colours)

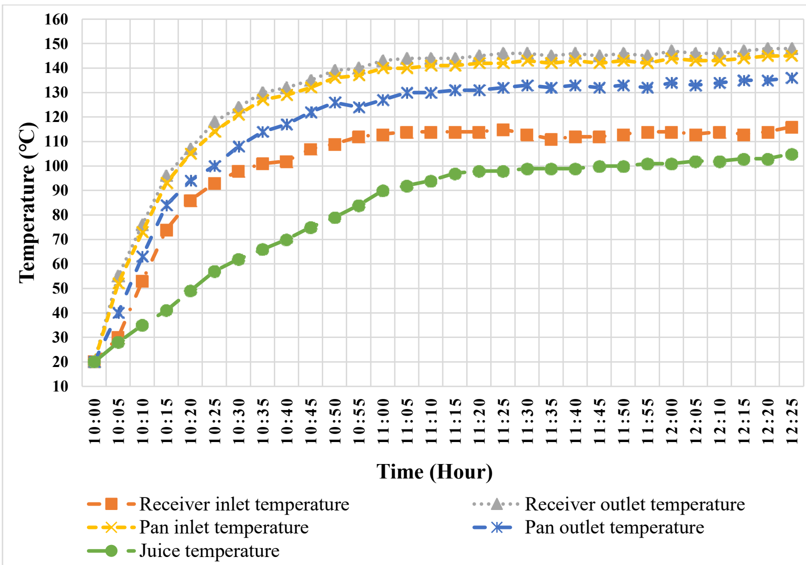


Figure 7 Average system energy and exergy efficiency for different tests (see online version for colours)

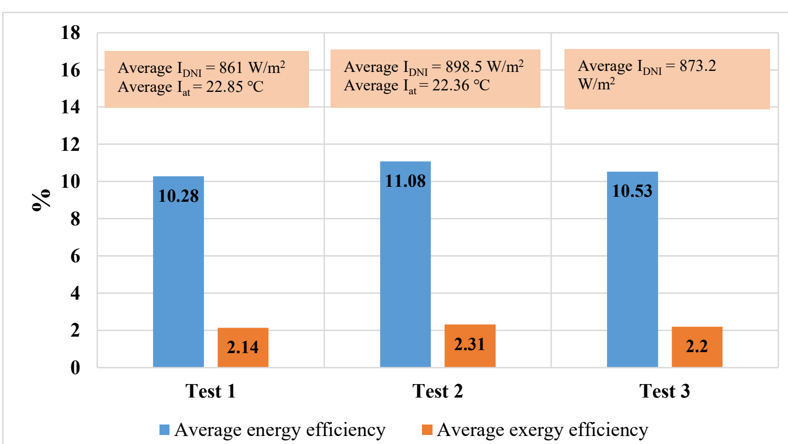


Table 3 Comparison of the present system with other pertinent suggested designs

Researcher	*The type of solar collector used*	*Aperture area*	*Temperature range*	*Working fluid*	*Application*	*Energy efficiency*	*Exergy efficiency*
Chaudhary and Yadav (2021)	Evacuated tube solar collector	2.8 m^2	105.4°C	HTF	Indirect concentrated sugarcane juice-making	-	11.39 W (Peak exergy power)
Singh (2021)	PDC	0.502 m^2	122°C	HTF	Indirect solar cooking (boiling)	6.96%–21.01%	0.02%–1.96%
Hosseinzadeh et al. (2021)	PDC	1.13 m^2	100°C	HTF with nanofluid	Indirect solar cooking (boiling)	12.85%–17.12%	1.26%–1.87%
Pawar et al. (2022)	Scheffler solar concentrator	16 m^2	118°C	Steam	Indirect jaggery making (steaming)	63.5%	-
Present system	PDC	2.626 m^2	105°C	HTF	Indirect liquid-jaggery making	10.28%–11.08%	2.14%–2.31%

4.4 Energy and exergy efficiency

The cooking pan in an indirect solar cooker cannot utilise the complete amount of thermal energy received. As a result, the fluid temperature increases throughout the testing period at both the outlet and inlet of the receiver. Therefore, the receiver's thermal power output increases due to the increased HTF temperature difference during the testing period. The mean thermal power output of the receiver is 981.83 W, 948.63 W, and 947.97 W for tests 1, 2, and 3, respectively. For tests 1, 2, and 3, the mean energy efficiency of the PDC was found to be 41.85%, 40.70%, and 43.90%, respectively. The solar DNI and ($T_{r,out} - T_{r,in}$) influence the receiver's average energy efficiency. For tests 1, 2, and 3, the receiver's average output thermal exergy rate is 228.04 W, 235.11 W, and 226.73 W. The calculated average exergy efficiencies of the PDC for tests 1, 2, and 3 are 10.97%, 10.82%, and 10.74%, correspondingly. The values of solar DNI, ($T_{r,out} - T_{r,in}$), and $T_a In$ ($T_{r,out}/T_{r,in}$) influence the average exergy efficiency of the receiver. The cooking pan exhibited an average output thermal power of 44.53 W, 50.24 W, and 46.34 W across tests 1, 2, and 3, respectively. The cooking pan achieved average energy efficiencies of 52.48%, 55.69%, and 54.67% for tests 1, 2, and 3, respectively. The solar DNI and the values of ($T_{c,in} - T_{c,out}$), ($T_f - T_i$), and ($T_s - T_i$) influence the average energy efficiency of the cooking pan. The cooking pan's average output thermal exergy rate is 228.04 W, 235.11 W, and 226.73 W for tests 1, 2, and 3. The average exergy efficiency of the cooking pan for tests 1, 2, and 3 are obtained as 40.98%, 41.35%, and 41.76%, respectively. Figure 7 compares the system's overall average energy and exergy efficiency for various tests. The study revealed that the pump's power use was negligible compared to the solar cooker's output power. In contrast to test 1, which had the lowest overall average energy (10.28%) and exergy efficiencies (2.14%), test 2 had the highest overall average energy (11.08%) and exergy efficiencies (2.31%). The overall average energy efficiency for all the tests depends upon the ($T_f - T_i$), ($T_s - T_i$), and the solar DNI. The average exergy efficiency for all the tests depends upon ($T_f - T_i$), ($T_s - T_i$), $T_a.ln.$ (T_f/T_i), and $T_a.ln.$ (T_s/T_i).

A comparison of the present system with earlier studies has also been performed, listed in Table 3. It has been found that the current system is on par with other suggested methods by other researchers after evaluating the various parameters.

5 Conclusions

This research conducts experiments over three consecutive days to determine the energy and exergy efficiencies of a novel indirect SLJMS using 1 kg of sugarcane juice. It has been discovered that the current technique is capable of manufacturing liquid jaggery. Based on the analysis performed, the following conclusions have been drawn:

- In test 1, the maximum T_{focus} achieved was 661°C at noon. The HTF took 20 minutes to attain a temperature of 100°C. The lowest average energy and exergy efficiencies, 10.28% and 2.14%, respectively, were achieved in this test. The time required by the system to produce liquid jaggery was 150 minutes, and 0.225 kg was produced.
- In test 2, it took 135 min to produce 0.212 kg of liquid jaggery from 1 kg sugarcane juice. At 11:40 h, when the solar DNI reached its peak value of 923 W/m^2, the

maximum T_{focus} and T_{co} were 685°C and 153°C. The maximum average energy and exergy efficiencies, 11.08% and 2.31%, respectively, were achieved in this test.

- In test 3, the highest T_{focus} and T_c were 685°C and 148°C, respectively, with solar DNI of 893 W/m^2 at 12:25 h. The average energy and exergy efficiencies gained were 10.53% and 2.2%, respectively. It was observed that it took 145 minutes to make 0.22 kg of liquid jaggery from 1 kg of sugarcane juice.
- The average energy efficiency in test 2 was found to be increased by 7.22% and 4.96% compared to test 1 and test 3. The average exergy efficiency in test 2 was also increased by 7.35% and 4.76% compared to test 1 and test 3.
- The findings show that exergy and energy efficiency changes depend entirely on solar DNI, ambient temperature, HTF temperature, wind speed, and sugarcane juice quality.

Acknowledgements

The authors wish to acknowledge Hindustan Petroleum Corporation Limited, Chandigarh, India, for its assistance with this investigation.

References

Aramesh, M., Ghalebani, M., Kasaeian, A., Zamani, H., Lorenzini, G., Mahian, O. and Wongwises, S. (2019) 'A review of recent advances in solar cooking technology', *Renew. Energy*, Vol. 140, pp.419–435, https://doi.org/10.1016/j.renene.2019.03.021.

Chaudhary, R. and Yadav, A. (2021) 'Experimental investigation of solar cooking system based on evacuated tube solar collector for the preparation of concentrated sugarcane juice used in jaggery making', *Environ. Dev. Sustain.*, Vol. 23, pp.647–663, https://doi.org/10.1007/s10668-020-00601-8.

Dhiman, A. and Sachdeva, G. (2023) 'Experimental investigation of an indirect-type solar cooker for indoor cooking based on a parabolic dish collector', *Heat Transf.*, Vol. 52, pp.378–394, https://doi.org/10.1002/htj.22699.

Harmim, A., Merzouk, M., Boukar, M. and Amar, M. (2013) 'Design and experimental testing of an innovative building-integrated box type solar cooker', *Sol. Energy.*, Vol. 98, pp.422–433, https://doi.org/10.1016/j.solener.2013.09.019.

Hosseinzadeh, M., Sadeghirad, R., Zamani, H., Kianifar, A., Mirzababaee, S.M. and Faezian, A. (2021) 'Experimental study of a nanofluid-based indirect solar cooker: energy and exergy analyses', *Sol. Energy Mater. Sol. Cells.*, Vol. 221, p.110879, https://doi.org/10.1016/j.solmat.2020.110879.

Hugot, E. (1986) *Handbook of Cane Sugar Engineering*, 1st ed., Elsevier Publishing Company, New York, https://doi.org/10.1016/0144-4565(86)90047-8.

Jakkamputi, L.P. and Mandapati, M.J.K. (2016) 'Improving the performance of jaggery making unit using solar energy', *Perspect. Sci.*, Vol. 8, pp.146–150, https://doi.org/10.1016/j.pisc.2016.04.019.

Kamboj, V., Agrawal, H., Malan, A. and Yadav, A. (2021) 'Thermal performance of the steam boiler based on Scheffler solar concentrator for domestic application: experimental investigation', *Aust. J. Mech. Eng.*, Vol. 19, pp.521–531, https://doi.org/10.1080/14484846.2019.1656148.

Khattak, S., Greenough, R., Sardeshpande, V. and Brown, N. (2018) 'Exergy analysis of a four pan jaggery making process', *Energy Reports*, Vol. 4, pp.470–477, https://doi.org/10.1016/j.egyr.2018.06.002.

Kumar, R. and Kumar, M. (2018) 'Upgradation of jaggery production and preservation technologies', *Renew. Sustain. Energy Rev.*, Vol. 96, pp.167–180, https://doi.org/10.1016/j.rser.2018.07.053.

Kumar, V., Chandrashekara, M. and Yadav, A. (2023) 'Experimental investigation of solar-powered food steamer based on parabolic dish concentrator for domestic applications', *Heat Transf.*, Vol. 52, pp.2796–2837, https://doi.org/10.1002/htj.22805.

La Madrid, R., Marcelo, D., Orbegoso, E.M. and Saavedra, R. (2016) 'Heat transfer study on open heat exchangers used in jaggery production modules – computational fluid dynamics simulation and field data assessment', *Energy Convers. Manag.*, Vol. 125, pp.107–120, https://doi.org/10.1016/j.enconman.2016.03.005.

Marie, L.F., Raj, S.P., Sai, P.V., Macleod, T., Srinivas, M., Srinivas Reddy, K. and O'Donovan, T.S. (2020) 'Solar thermal heating and freeze concentration for non-centrifugal sugar production: design and performance analysis', *Energy Eng. J. Assoc. Energy Eng.*, Vol. 117, pp.323–342, https://doi.org/10.32604/EE.2020.011035.

Pawar, J.B., Chavhan, G.R. and Nukulwar, M.R. (2022) 'Experimental performance analysis of 16 m2 solar Scheffler system for jaggery making', *Mater. Today Proc.*, Vol. 63, pp.479–486, https://doi.org/10.1016/j.matpr.2022.03.645.

Shanmugan, S., Rajamohan, P., Mutharasu, D. and Ibrahim, K. (2014) 'Performance evaluation of an acrylic mirror booster solar still for neera concentration in jaggery-making industry', *Int. J. Sustain. Energy*., Vol. 33, pp.261–272, https://doi.org/10.1080/14786451.2011.644852.

Sharma, S.D., Iwata, T., Kitano, H. and Sagara, K. (2005) 'Thermal performance of a solar cooker based on an evacuated tube solar collector with a PCM storage unit', *Sol. Energy*., Vol. 78, pp.416–426, https://doi.org/10.1016/j.solener.2004.08.001.

Singh, H., Gagandeep, Saini, K. and Yadav, A. (2015) 'Experimental comparison of different heat transfer fluid for thermal performance of a solar cooker based on evacuated tube collector', *Environ. Dev. Sustain.*, Vol. 17, pp.497–511, https://doi.org/10.1007/s10668-014-9556-3.

Singh, O.K. (2021) 'Development of a solar cooking system suitable for indoor cooking and its exergy and enviroeconomic analyses', *Sol. Energy*., Vol. 217, pp.223–234, https://doi.org/10.1016/j.solener.2021.02.007.

Stumpf, P., Balzar, A., Eisenmann, W., Wendt, S., Ackermann, H. and Vajen, K. (2001) 'Comparative measurements and theoretical modelling of single-and double-stage heat pipe coupled solar cooking systems for high temperatures', *Sol. Energy*., Vol. 71, pp.1–10, https://doi.org/10.1016/S0038-092X(01)00026-3.

Tiwari, G.N., Kumar, S. and Prakash, O. (2003) 'Study of heat and mass transfer from sugarcane juice for evaporation', *Desalination*, Vol. 159, pp.81–96, https://doi.org/10.1016/S0011-9164(03)90047-6.

Appendix A

Theoretical calculations for indirect SLJMS.

The specific heat of liquid jaggery ($C_{pL,Jag}$) is calculated by the expression given:

$$C_{pL,Jag} = (1 - 0.006 \times B_{LJ}) \times 4.1868 \tag{A1}$$

As dissolved material has the same weight before and following evaporation, we may compare these values and calculate the final brix of liquid syrup (B_{LJ}) solution as follows:

$$J \times B_{SJ} = S \times B_{LJ} \tag{A2}$$

B_{LJ} is the final brix of liquid jaggery, J is the weight of sugarcane juice (kg), B_{SJ} is the brix of sugarcane juice, and S is the weight of liquid jaggery. The two primary ingredients of sugarcane juice, sucrose and water, have different specific heat values: sucrose has 1.24 kJ/kg K while water is 4.187 kJ/kg K. When sucrose is eliminated from sugarcane juice, a compromise between the resulting specific heat values, which can be computed using equation (A1), occurs because water has a more excellent specific heat than sucrose. Equation (A2) determines the values of B_{LJ}, and by using these values in equation (A1), the value of specific heat is calculated, which is listed in Table A1.

Table A1 Measurement data for the specific heat of liquid jaggery

Mass of sugarcane juice, m_J (kg)	*Sugarcane juice Brix, B_{SJ}*	*Mass of liquid jaggery (kg)*	*Liquid jaggery brix, B_{LJ}*	*Specific heat of liquid jaggery, $C_{pL,Jag}$ (kJ/kg.K)*
1	13	0.225	57.78	2.7354
1	13	0.212	61.32	2.6464
1	13	0.220	59.09	2.7024

Appendix B

Results and discussion

In this section, the time-dependent variation graphs of ambient temperature, focus temperature, wind speed, and DNI have been presented. Figure B1 depicts the time-dependent variations of the solar DNI and ambient temperature during the heating of 1 kg of sugarcane juice on 23/11/2022. The maximal solar DNI was recorded as 881 W/m^2 at 12:10 h. Figure B2 shows the time-dependent variations of T_{focus} and wind speed during the heating of 1 kg of sugarcane juice on 23/11/2022.

Figure B3 depicts the time-dependent variations of the solar DNI and ambient temperature during the heating of 1 kg of sugarcane juice on 24/11/2022. The average solar DNI was observed as 898.5 W/m^2. Figure B4 shows the time-dependent variations of T_{focus} and wind speed during the heating of 1 kg of sugarcane juice on 24/11/2022. It has been observed in this test also that the T_{focus} varies as the wind speed increases. Figure B5 depicts the time-dependent variations of the solar DNI and ambient temperature during the heating of 1 kg of sugarcane juice on 25/11/2022. Throughout the procedure, the solar DNI ranged between 826 and 893 W/m^2. Figure B6 shows the time-dependent variations of T_{focus} and wind speed during the heating of 1 kg of sugarcane juice on 25/11/2022. It has been observed in this test also that the T_{focus} varies as the wind speed increases.

Figure B1 Time-dependent variations of solar DNI and T_{at} during the heating of 1 kg of sugarcane juice on 23/11/2022 (see online version for colours)

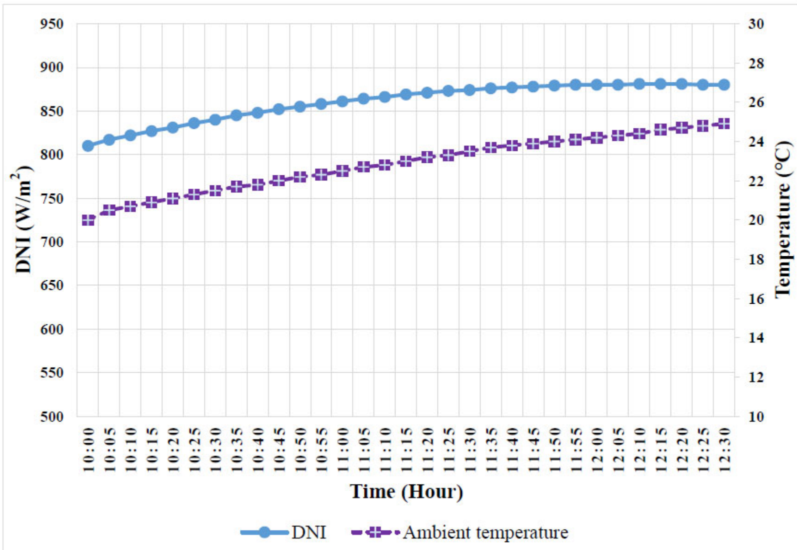


Figure B2 Time-dependent variations of T_{focus} and wind speed during the heating of 1 kg of sugarcane juice on 23/11/2022 (see online version for colours)

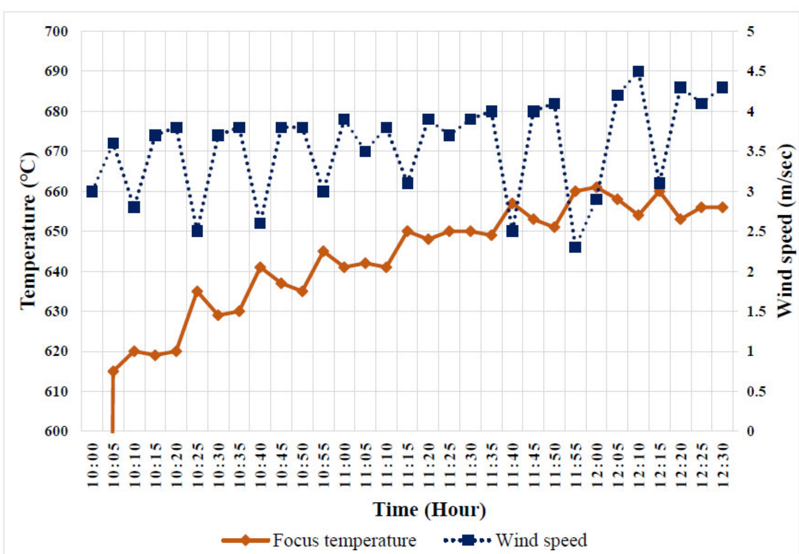


Figure B3 Time-dependent variations of solar DNI and ambient temperature during the heating of 1 kg of sugarcane juice on 24/11/2022 (see online version for colours)

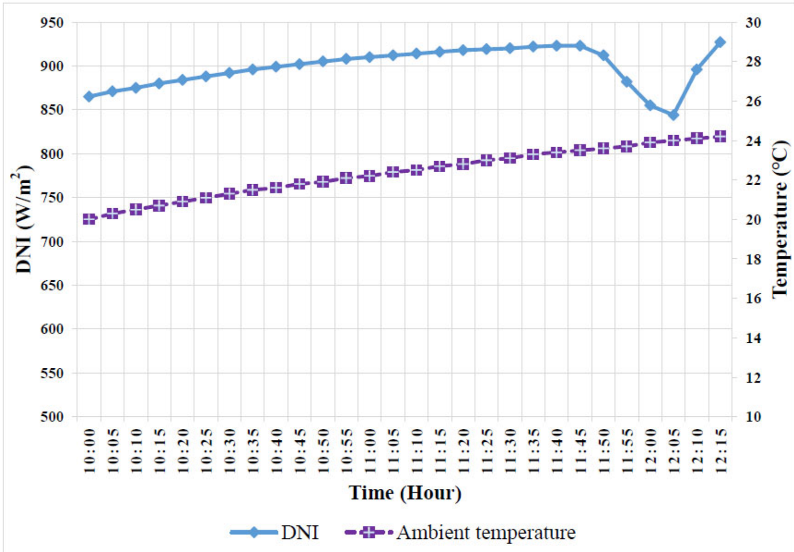


Figure B4 Time-dependent variations of T_{focus} and wind speed during the heating of 1 kg of sugarcane juice on 24/11/2022 (see online version for colours)

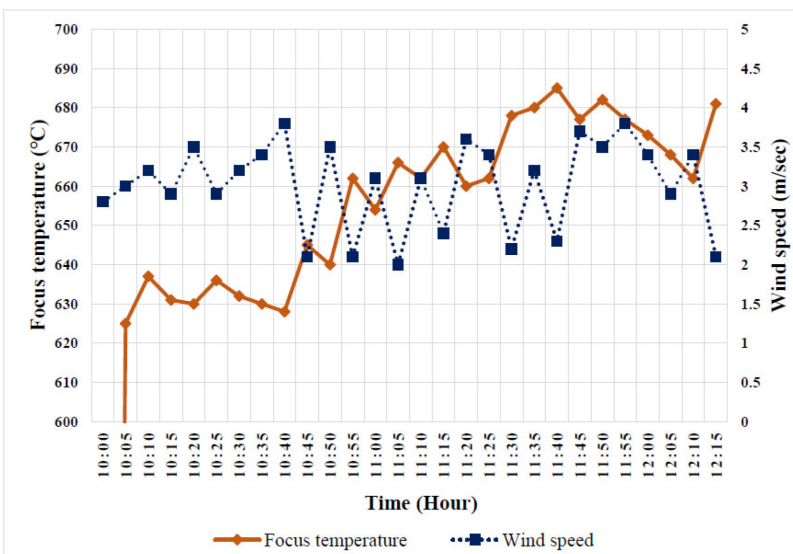


Figure B5 Time-dependent variations of solar DNI and ambient temperature during the heating of 1 kg of sugarcane juice on 25/11/2022 (see online version for colours)

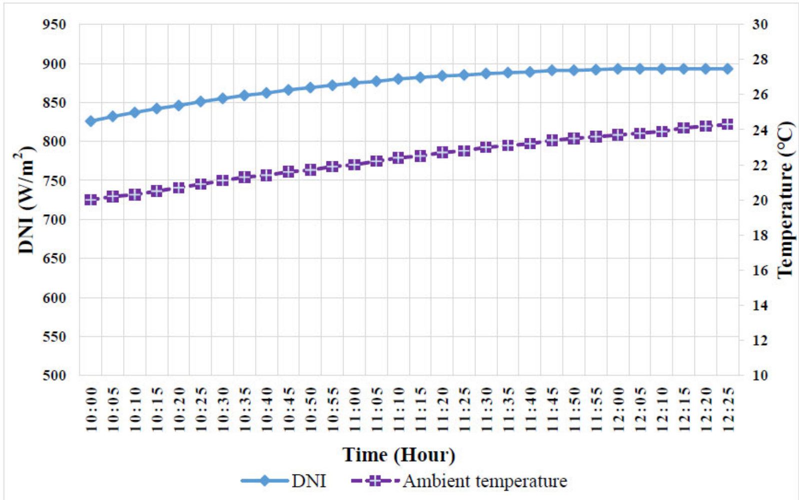


Figure B6 Time-dependent variations of T_{focus} and wind speed during the heating of 1 kg of sugarcane juice on 25/11/2022 (see online version for colours)