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Experimental Investigation of an Oil-Based Heat Pipe Evacuated Tube Collector for Cooking Application

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ABSTRACT

This study focuses on integration of solar thermal evacuated tube collectors for clean energy cooking, aligning with the Sustainable Development Goals. The system is designed to heat oil instead of water, creating a hot reservoir for heat extraction and cooking. The complete system comprises solar thermal collectors, heat transfer oil, a storage tank, a cooking vessel, a control system, and valves. The maximum observed temperature was about 186 °C with an oil-based solar thermal collector whose average efficiency was 29 %. The performance of the solar collectors depends on the global solar irradiance incident on the heat pipes. This paper therefore, presents the experimental results of a heat pipe-evacuated solar thermal collector.

Keywords: Heat pipe-evacuated solar tube collector; solar cooking; and solar thermal.

NOMENCLATURE

Abbreviations	
DFET	Direct Flow Evacuated Tube
ECT	Evacuated Tube Collector
IEA	The International Energy Agency
HPETC	Heat Pipe Evacuated Tube
LPG	Liquefied Petroleum Gas
PCM	Phase Change Material
PV	Photovoltaic
USB	Universal Serial Bus
Symbols	
°C	Degrees Celsius
A_{ri}	Collector area
Fr	Efficiency factor
G_T	Solar radiation
$(\tau\alpha)_e$	transmittance absorptance
U_L	heat loss coefficient
T_a	Ambient temperature
T_m	average temperature of the absorber
E_{out}	Useful energy
E_{in}	Absorbed energy
Q_u	Useful power
$\dot{m}$	Mass flow rate
c	The heat capacity of the fluid
T_1	The inlet temperature of the fluid
T_2	Outlet temperature of the fluid
A_{cl}	Collector surface area
η	Collector efficiency
a_1 and a_2	Collector coefficient obtained from experiments

1. INTRODUCTION

Cooking energy accounts for 90 % of energy consumption in developing countries. According to the International Energy Agency (IEA, 2020), over 2.6 billion people lack access to clean cooking technologies, with 900 million living in Sub-Saharan Africa. Only 17% of this region´s population has access to clean cooking solutions. This has led to approximately half a million premature deaths annually, primarily among women and children. There is a global push for transitioning from fossil-based energy to renewables. In developing countries, traditional biomass remains the primary energy source (Energypedia, 2018).

Mozambique, despite its abundant energy resources, has only 42 % of its population connected to the national grid. Outside major cities, 65 % of the population relies on fuelwood for cooking. In Maputo, 65 % use charcoal, while 21 % use LPG. In Matola, 38 % use charcoal, and 7.7 % use LPG. LPG usage outside these cities is minimal, limited to only 0.4 % of the population (Sakyi-Nyarko, 2022).

Burning biomass in traditional stoves releases harmful smoke, causing respiratory diseases and contributing to 1.6 million premature deaths annually. Developing countries, particularly in Africa, have an opportunity to

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leapfrog fossil fuels by adopting green energy technologies for cooking (Mandelli et al., 2014). There is a pressing need for affordable, efficient, and innovative renewable energy solutions tailored to the challenges of dispersed populations with low purchasing power.

In this context, Eduardo Mondlane University in Mozambique is developing an indirect oil-based solar cooking system. The system includes a cold storage tank, a heat pipe evacuated solar thermal collector for preheating heat transfer fluid, thermal hot storage, PV panels for energy top-up, load control, heating elements, and a cooking vessel.

2. SOLAR THERMAL COLLECTORS

Solar thermal collectors convert solar radiation into useful heat for various applications (Kumar & Rosen, 2011). They can be concentrating or non-concentrating. Non-concentrating collectors, such as flat plate and evacuated tube collectors, have the absorber as the solar radiation intercepting area. Concentrating solar collectors, like parabolic troughs and central tower systems, focus solar radiation onto a smaller area, achieving higher temperatures (up to 1000°C) compared to non-concentrating collectors (below 200°C) (Dincer, 2013). This study focuses only on evacuated tubes.

2.1 Working principle of evacuated tube and application

Evacuated tube collectors (ETC) are the most predominant solar thermal technology worldwide with a share of about 70% capacity (Huang et al., 2019; Kumar & Rosen, 2011). Many researchers have reviewed evacuated tube collectors (Sabiha et al., 2015). ETC comprehends a flat or curved absorber enclosed with a selective surface and fluid inlet and outlet piping (Dincer, 2013). ETC encompasses two sealed concentric tubes, in such a way that between the inner and outer tube, there is no air. The function of the vacuum is to enhance the thermal performance by eliminating the convection losses and, thus, improving the thermal insulation. The outer tube is transparent to incoming solar radiation, but it does not allow the long wave radiation to escape. The inner tube is prepared with high-absorbing material and a low-emitting coating material so that it absorbs much of the incident solar irradiance and transfers the heat to the circular aluminium fin and heat pipe inside it. The heat pipe contains a working medium, when heated, it evaporates, rising to the top of the heat pipe carrying a large amount of energy. The vapour condenses and returns to the lower part of the heat pipe in a cyclic process. The inner tube is in touch with an aluminum fin which transfers the heat to the heat pipe by conduction. There are two types of evacuated tube collectors: a) direct flow evacuated tube (DFET) and b) heat pipe evacuated tube (HPET). In DFET, the fluid of the solar loop flows through the piping of the absorber. The collector has a U-U-bend tube instead of the heat pipe. The cold fluid enters by one end, and it is heated up and goes out by the other end. The tube is divided by the heat-absorbing reflective plate, which separates the in-flow and the return section. In HPET, the absorbed heat is transferred using the heat pipe principle where there is no direct interaction with the working fluid of the solar loop (Dincer, 2013; Lecturer & Mohammed, 2014).

Many scholars have studied many issues related to evacuated tube solar collectors (Siuta-Olcha et al., 2021, ; Zubriski & Dick, 2012); (Arora et al., 2011; Olek et al., 2016; Zubriski & Dick, 2012)); ((Abdulhussain, 2018; Nájera-Trejo et al., 2016; Picón-Núñez et al., 2016; Vijayakumar et al., 2017). There are several factors affecting the performance of evacuated tube collectors such as working fluid, optical properties of the collector material, mass flow rate of working fluid, and collector size and inclination. Detailed effects of using different heat transfer mediums have been studied (Kumar & Rosen, 2011). The materials whose effects were studied are Air, water, thermal D 12, supercritical CO_2, glycol, R 134a, R 407C, R 22; Phase change material such as Tritriacontane and Erythritol and nanofluids such as CuO, Multiwall Carbon Nanotubes, SiO_2, TiO_2 and Al2O3 (Kumar & Rosen, 2011) (Abd-Elhady et al., 2018). The heating capability of evacuated tubes has been improved by a) filling heat transfer oil into the evacuated tube such that the oil is used as heat transfer from the inner surface to the heat pipe and b) replacing the finned surface with foamed copper. Nanofluids perform better than other materials, but is not recommended for direct-flow evacuated tubes (Abd-Elhady et al., 2018). Papadimitratos et al., (2016) studied the contribution of phase change material.

PCM such as Tritriacontane and Erythritol with melting temperatures between 72 °C and 118 °C was incorporated inside the inner tubes of evacuated tube solar collectors. The research reveals substantial efficiency enhancement for both normal and stagnation operations.

Detailed components of the evacuated tube collector are shown in Figure 1.

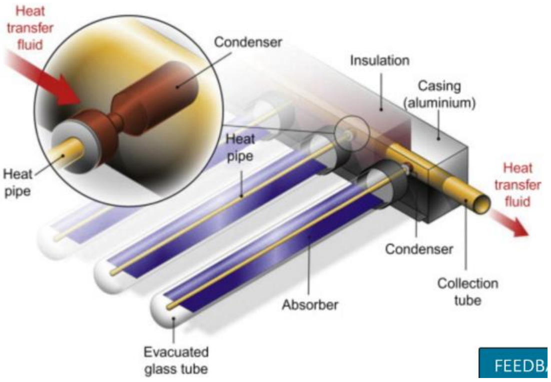

Figure 1: Evacuated tube collector components

Source: (Dincer, 2013)

2.2 *Evacuated tube application*

Evacuated tube collectors can be used for many heating and cooling applications for both residential and industrial sectors. For the residential sector, they can be applied for water heating, air conditioning, and solar cookers. In industry, they can be used in drug and pharmaceutical firms, textiles, paper, leather, and swimming pools. Their specific application industry heat engines, desalination, solar drying, and steam generation, among others (Sabiha, 2014).

3. MATERIAL AND METHODS

A commercial heat pipe evacuated tube solar collector with an aperture area of 1.39 m^2 and an absorber area of 1.21 m^2, comprising fifteen heat pipe evacuated tube collectors, has been tested. Table 1 gives the detailed characteristics of the evacuated tube collector. The cold storage has been placed on the top of a metal structure of 3 m in height. Logging equipment was coupled to the system. A heat transfer B22 Fuchs oil has been used as the working fluid.

Table 1: Characterization of the solar collector

Characteristics of the collector			
Number of tubes	15	Material	Borosilicate glass Pipe
connections	0.22 m	The diameter of the cover tube	0.58 m
Pressure resistance	6 Bar	The diameter of the absorber tube	0.47 m
Freezing tolerance	- 35 °C	Glass thickness	0,22 m
Stagnation Temperature	250 °C	Absorptive coefficient	0.94-0.96
Heat transfer medium	Water-glycol solution	Heat pipe copper Emissivity coefficient	< 0.06 (0.04- 0.06)
Fin	aluminum	Vacuum	< 3x10-4 Pa

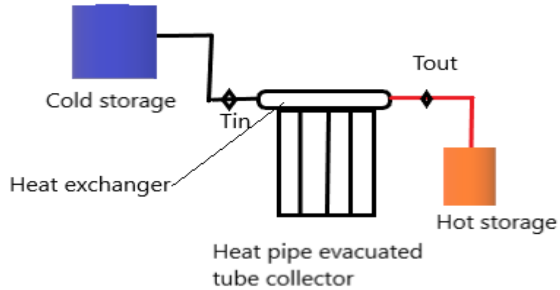

Figure 2: Experimental Setup

The experimental setup (Figure 2) encompasses the storage tank, heat pipe evacuated tube solar collector, and logging equipment (computer, datalogger, thermocouples, and solar cell). In this setup, the outlet pipe is closed and the oil flows by gravity to the manifold. When the pipe is full with oil, the inlet side is closed. By this time the temperature rises until the outlet valve is open and the hot oil goes out. This is repeated many times.

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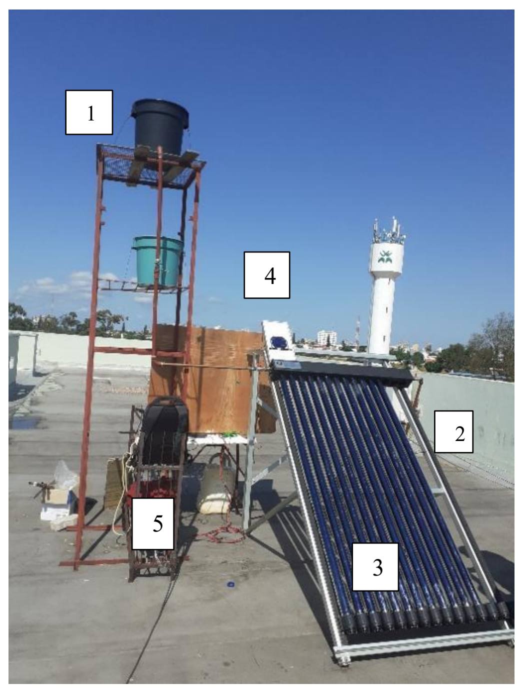

Figure 3: Testing setup

The system consists of two storage tanks, one for cold oil-1 and the other for hot oil-2, the heat pipe evacuated tube collector-3, PV panel-4, and logging equipment-5. The oil flows by gravity from the cold tank to the heat pipe evacuated tube when the valve is opened, and it passes through the manifold where it heats up and then goes down to the hot storage tank. The actual experiment setup is presented in Figure 3. The test was performed on the 23rd of March 2022 and the 26th of April 2022 at Eduardo

Mondlane University, the main campus located in Maputo City. The experiment was set at the top of the Faculty of Science, Department of Physics, with a latitude of minus 25.95100 and a longitude of 32.59906. The university is located in the coastal area

3.1. Solar radiation and temperature measurement

For solar radiation and temperature measurement, a datalogger with an uncertainty of 0.06 % from the National Instruments model NI USB-9211 was used. This device is connected to the computer by a USB cable and using LabVIEW software performs the visualization and data acquisition of solar radiation and ambient temperatures. A Si-mono crystalline technology cell was used as a global radiation measurement sensor and a K-type thermocouple was used for temperature. The solar cell is calibrated such that 30 mV corresponds to 1000 W/m^2. The data logger was set in a way that the sensor takes measurements every 10 seconds. The solar radiation incident on the solar cell is obtained by taking the I-V operating parameters of the solar cell, which are initially converted into STC reference parameters (Temperature=25 and radiation =1000 W/m^2) and using Kirchhoff´s relationship of currents.

3.2 Performance of Solar Thermal Collector

The performance of the solar collector is derived from the energy balance equation which is the statement of the first law of thermodynamics, i.e., energy conservation law, and is written as follows:

$$E_{in} = E_{out} \qquad \text{(eq. 1)}$$

E_{out} includes useful energy and losses. The useful energy is equal to the absorbed energy by the collector. The useful power is defined as:

$$Q_u = \dot{m}c(T_2 - T_1) \qquad \text{(eq. 2)}$$

Where $\dot{m}$ is the mass flow rate of the working fluid, c is the heat capacity of the fluid, T_1 is the inlet temperature and T_2 is the outlet temperature.
The absorbed energy is given by:

$$Q_u = A_{cl}F_RG_T \ (\tau\alpha)_e \text{ -}U_LA_{cl}(T_m - T_a) \qquad \text{(eq. 3)}$$

Where A_{cl} is the collector area, F_R is the efficiency factor, G_T is the solar radiation, *is* the transmittance absorptance, U_L is the heat loss coefficient, T_m is the average temperature of the absorber and T_a is the ambient temperature.

The ratio of the useful energy to solar radiation intercepted by the aperture area of the solar collector is called solar collector efficiency, and is given by:

$$\eta = \frac{Q_u}{A_{cl}G_T} = \frac{\dot{m}c_p(T_2-T_1)}{A_{cl}G_T} = F_R(\tau\alpha)_e - \frac{U_L(T_m-T_a)}{A_{cl}G_T} \qquad \text{(eq. 4)}$$

The efficiency of the collector is plotted against $(T_m\text{-}T_a)/G_T$ and the linear relation between both parameters can be represented according to equation 5:

$$\eta_c = \eta_o - a_1\frac{(T_m-T_a)}{G_T} - a_2\frac{(T_m-T_a)^2}{G_T} \quad \text{(eq. 5)}$$

4. RESULTS

Figure 4 and Figure 5 show the profile of the Global horizontal radiation recorded on the 26th of April 2022 and 23rd of March 2022 at Eduardo Mondlane University, the main campus located in Maputo City respectively. The university is located in the coastal area. The behaviour of solar radiation on the day the experiment was carried out is shown in Figure *4*:

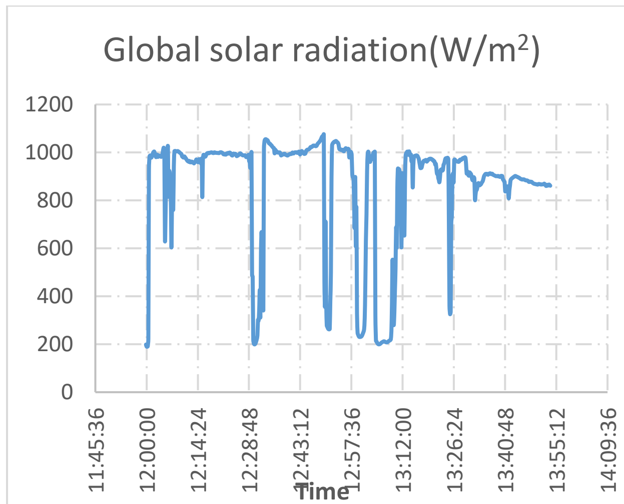

Figure 4: Solar radiation on 26th April 2022

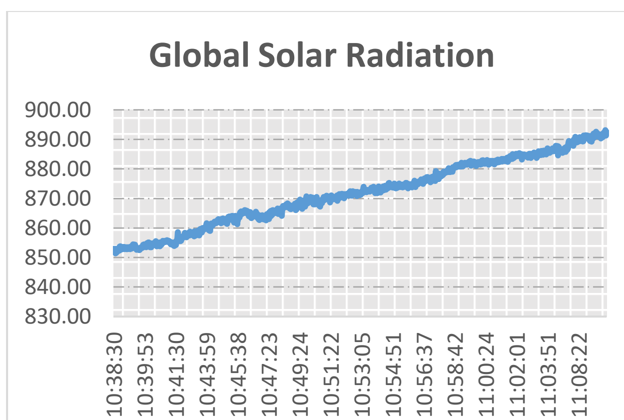

Figure 5: Solar radiation on 23rd March 2022

4.2. Water-based

The heat pipe evacuated tube has been designed for water heating purposes, therefore, the first test was done using water as the heat transfer fluid. The results of the water-based heat pipe evacuated tube are shown in Figure 6.

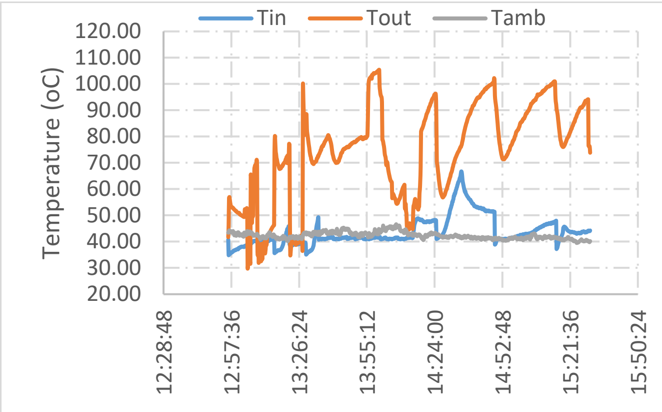

Figure 6: Heating water with evacuated tubes. The temperatures are Tin: inlet to the heater, Tout: outlet of the heater, and Tamb: ambient temperature.

4.3. Oil-based heat pipe evacuated tube collector

In this test, water was replaced by heat transfer oil, and the measurements were performed with an oil flow rate of 0,11 l/min. The results of the oil-based heat pipe evacuated tube collector are shown in Figure 7.

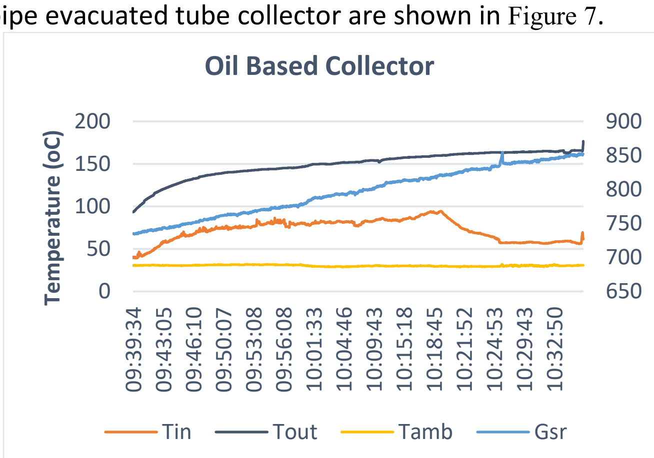

Figure 7: Heating oil with evacuated tubes. The temperatures are T_{in}: inlet to the heater, Tout: outlet of the heater, and T_{amb}: ambient temperature

4.3. Collector Performance

The collector efficiency was computed using Equation 4. The mass flow rate was 0,0018 litres per second. Important parameters were calculated and organized in **Erro! Fonte de referência não encontrada.**.

Table 1: Efficiency and other parameters at a mass flow rate of 0,0018 *litres* per second

	T_{in}	T_{out}	T_{amb}	***Read***	**Effic**
Avera	39,10	92,96	28,53	734,03	0,21
Maxi	94,36	176,75	31,75	854,63	0,40
Mini	71,83	148,93	30,15	796,27	0,29

5. DISCUSSION

The experimental results demonstrate the performance of the heat pipe evacuated solar thermal collector under varying conditions, as illustrated in Figures 4, 5, 6, and 7. The discussion is structured around the key observations from data, including solar radiation patterns, temperature profiles, and collector efficiency.

5.1 Solar Radiation Patterns

As shown in Figures 4 and 5, the solar radiation data reveal significant differences between cloudy and clear sky conditions. On April 26, 2022 (Figure 4), the solar radiation fluctuated between 200 W/m^2 and 1000 W/m^2, with frequent oscillations due to intermittent cloud cover. In contrast, on March 23, 2022 (Figure 5), the solar radiation exhibited a more stable pattern, with fewer peaks and lows, indicating a clear sky day. This stability in solar radiation on clear days enhances the performance of the heat pipe evacuated tube collector, as consistent energy input allows for more efficient heat transfer and higher temperature.

5.2 Water-Based Performance

The water-based tests, depicted in Figure 6, highlight the system´s ability to heat water efficiently. On the day of the test, the temperatures were close to 40 °C, and the system achieved the boiling point of water (100 °C) under normal atmospheric pressure. The heating cycles, which averaged 7 minutes per litre of water, demonstrated the rapid heating capability of the evacuated tube collector. This aligns with previous studies (Hlaing & Soe, 2014), which have shown that heat pipe evacuated tube collectors are effective for quick water heating, making them suitable for applications such as hot water supply in supermarkets, health centres, and residential settings.

5.3 Patterns Oil-based Performance

When heat transfer oil replaced water in the system, it achieved significantly higher temperatures, reaching up to 180 °C (See **Erro! Fonte de referência não encontrada.**). This increase in temperature is due to the oil´s higher boiling point and better thermal stability compared to water. However, the elevated temperatures also resulted in increased manifold pressure, which required the implementation of safety measures to prevent system failure. These results align with the findings of Al-Azmi (2022), who reported that heat pipe evacuated tube collector can produce fluid temperatures exceeding 200 ˚C under optimal conditions.

5.4 Collector Efficiency

The oil-based collector efficiency, calculated using Equation 4 and summarized in Table 2, varied between 21 % and 40 % with an average efficiency of 29 %. The maximum efficiency of 40 % was achieved under conditions of higher solar radiation and flow rates mentioned above. However, substantial heat losses were observed, primarily due to the heat exchangers and the storage's lack of insulation. These losses highlight the need for improved insulation to enhance system performance and efficiency.

The efficiency values fall within the acceptable range for heat pipe solar thermal collectors, which typically operate at efficiencies of 20 °C or higher (Galhe et al., 2020; Mehla & Kumar, 2021). The results suggest that while the system is effective, there is room for improvement, particularly in minimizing heat losses and optimizing the flow rate of the heat transfer fluid.

5.5 Implications for Solar Cooking

The ability of the system to achieve oil temperatures above 170 °C makes it a promising solution for solar cooking applications. However, the variability of solar radiation and the associated heat losses indicate that additional energy sources, such as photovoltaic (PV) panels, may be required to ensure consistent performance, especially during periods of low solar radiation. A backup energy source, such as hydrokinetic, wind, or sustainable biomass, could further enhance the system´s reliability and usability in off-grid or rural settings.

6. CONCLUSION

The experimental results demonstrated that the heat pipe evacuated tube collector is capable of heating oil to temperatures suitable for cooking, with peak temperature reaching 180 °C. The system´s efficiency, while acceptable, could be improved through better insulation and optimized heat transfer fluid flow rates. The integration of PV panels or other renewable energy sources could provide the necessary top-up for more efficient cooking applications, particularly in regions and days with low solar radiation.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved this manuscript.

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