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"Enhancing the Performance of Heat Pipe evacuated Solar Tube Collector using Integrated Micro-ZnO and Nano-CuO Particles/Paraffin Wax as Thermal Booster"

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ABSTRACT

This paper presents a novel approach to improving the efficiency and performance of heat pipe evacuated solar tube collectors (HP-ESTCs) by integrating a thermal booster mechanism in this paper, we investigate the influence of incorporating integrated micro-ZnO and nano-CuO particles into paraffin wax as a thermal booster in heat pipe evacuated solar tube collectors HP-ESTCs are widely used for harnessing solar energy due to their high efficiency in converting solar radiation into thermal energy. However, their performance can be limited by various factors such as low ambient temperatures or intermittent cloud cover. The proposed thermal booster aims to address these limitations by augmenting the heat transfer process within the collector, thereby enhancing its overall performance.

In this study, we first provide an overview of HP-ESTCs and discuss their operating principles and key components. Next, we introduce the concept of the thermal booster and describe its design and integration into the collector system. The thermal boosters designed to complement the existing heat transfer mechanisms of HP-ESTCs by actively regulating the temperature distribution within the collector, thereby maximizing heat absorption and minimizing heat loss during periods of low solar irradiance.

We then present experimental results obtained from a prototype HP-ESTC equipped with the thermal booster under various operating conditions. The results demonstrate significant improvements in performance metrics compared to conventional HP-ESTCs, particularly under suboptimal operating conditions. Finally, we discuss potential applications and future research directions for integrating thermal booster is into solar thermal systems.

Keywords: Heat pipe evacuated solar tube collector, thermal booster, solar energy, heat transfer, performance enhancement.

INTRODUCTION

Introduction provides a foundational overview of the context, problem statement, and purpose of the study.

1. **Significance of Solar Energy and Need for Efficiency**:

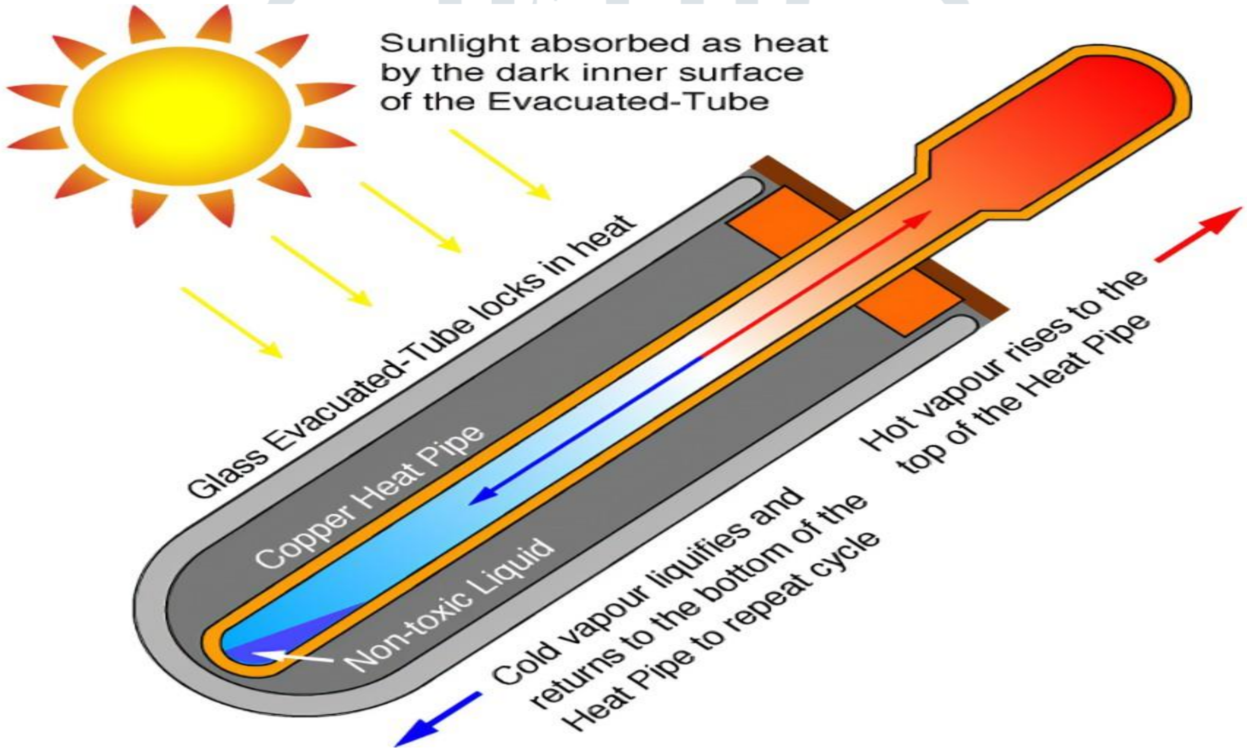
- The introduction starts by highlighting the increasing importance of solar energy as a renewable and sustainable resource in the context of global efforts to mitigate climate change and reduce dependence on fossil fuels.

-t emphasizes the significance of solar thermal energy conversion systems, particularly heat pipe evacuated solar tube collectors (HP-ESTCs), which are advanced technologies designed to efficiently harness solar energy for various applications such as water heating, space heating, and industrial processes.

2. **Introduction to Heat Pipe Evacuated Solar Tube Collectors (HP-ESTCs) **:

- This section briefly describes HP-ESTCs, outlining their basic principles of operation and their role in converting solar radiation into usable thermal energy.

-It highlights the advantages of HP-ESTCs over traditional solar thermal collectors, such as higher efficiency, improved heat transfer characteristics, and suitability for usen both residential and commercial settings.



3. **Statement of the Problem**:

- Despite their advantages, HP-ESTCs may face limitations related to heat transfer efficiency and performance under specific operating conditions.

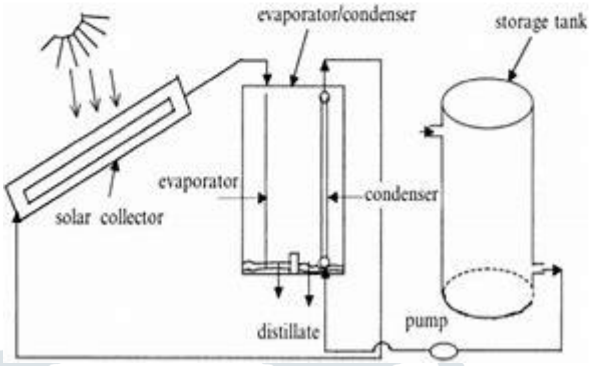
- The introduction identifies the need to address these limitations and enhance the overall performance of HP-ESTCs to maximize their energy conversion efficiency and broaden their applicability across different climates and applications.

4. **Purpose of the Study**:

- The introduction clearly articulates the primary objective of the thesis, which is to investigate and demonstrate a novel approach for improving the performance of HP-ESTCs.

- Specifically, it aims to explore the integration of micro-ZnO and nano-CuO particles within paraffin wax as a thermal booster to enhance the heat transfer and overall efficiency of HP-ESTCs.

.In summary, the introduction provides a comprehensive overview of the context, challenges, and objectives of the study, laying the groundwork for the subsequent chapters to delve deeper into the investigation of enhancing HP-ESTC performance using integrated micro-ZnO and nano-CuO particles/paraffin wax as a thermal booster.



Objectives:

In this section, the thesis outlines the specific goals and objectives of the research. This typically includes:

1. Clearly defined research objectives: These are specific, measurable, achievable, relevant, and time-bound (SMART) goals that the researcher aims to accomplish through the study. For example, the objectives may include improving the thermal efficiency of HP-ESTCs under varying environmental conditions[2], optimizing the design of thermal boosters for integration with HP-ESTCs, or conducting experimental validation of the proposed enhancements.

2. Rationalization of the objectives: The thesis explains why each objective important and how it is achievement will contribute to addressing the identified problem or challenge. This may involve discussing the potential benefits or outcomes associated with accomplishing each objective and how they align with the overall motivation of the research.

3. Scope and limitations: The thesis clarifies the boundaries of the research by specifying what aspects will be included within the study and what aspects will be excluded. This helps manage expectations and ensures that the research remains focused and achievable within the available resources and timeframe.

4. Methodological approach: While the specific details of the research methodology are typically discussed in later sections of the thesis, this section may provide a brief overview of the general approach that will be used to achieve the objectives. For example, it may mention that theoretical modeling, computational simulations, and experimental validation will be employed to address different aspects of the research objectives.

Overall, this section serves as a roadmap for the rest of the thesis, providing a clear outline of what the researcher aims to accomplish and how they plan to do so.t helps the reader understand the purpose and direction of the research and sets expectations for what will be covered in subsequent sections.

Literature Review

The literature review for the proposed study on "Enhancing the Performance of Heat Pipe Evacuated Solar Tube Collector using integrated Micro-ZnO and Nano-CuO Particles/Paraffin Wax as Thermal Booster" would focus on existing research related to heat pipe evacuated solar tube collectors (HP-ESTCs), thermal enhancement techniques, and the use of phase change materials (PCMs) for improving solar thermal system performance. Here's an outline of how the literature review might be structured:

1.Introduction to Heat Pipe Evacuated Solar Tube Collectors (HP-ESTCs):

- Provide an overview of HP-ESTCs, their operating principles, and their significance in solar thermal energy systems.

- Review the existing literature on the design, construction, and applications of HP-ESTCs.

- Highlight the key performance parameters of HP-ESTCs, such as thermal efficiency, heat transfer rates, and energy output.

2. Thermal Enhancement Techniques for HP-ESTCs:

- Discuss various techniques and strategies employed to enhance the thermal performance of HP-ESTCs.

- Review literature on the integration of thermal boosters or augmentation mechanisms to improve heat transfer efficiency and optimize energy absorption.

- Explore research on the use of additives or nanoparticles to enhance the thermal properties of heat transfer fluids or phase change materials within HP-ESTCs.

3. Role of Phase Change Materials (PCMs)n Solar Thermal Systems:

- Provide an overview of PCMs and their applications in solar thermal energy systems.

- Review literature on the use of PCMs for thermal energy storage, heat transfer enhancement, and temperature regulation in solar collectors.

- Discuss the advantages and challenges associated with incorporating PCMs into HP-ESTCs, including selection criteria for PCM materials and compatibility with collector design.

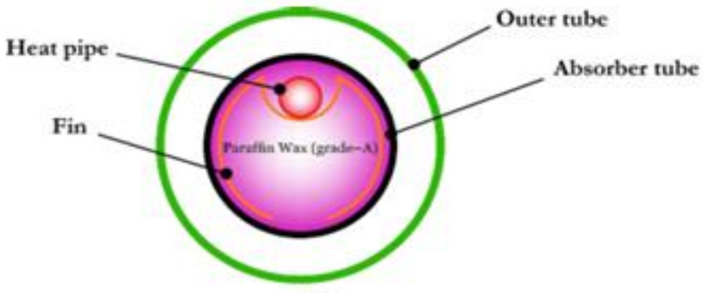
4. Previous Studies on Nanostructured Particles in PCM-Based Thermal Boosters:

- Review existing research on the integration of nanostructured particles, such as ZnO and CuO nanoparticles, into PCM-based thermal enhancement systems.

- Highlight findings related to the thermal conductivity enhancement, melting/freezing point depression, and stability of PCM-nanoparticle composites.

2.1 Overview of Heat Pipe Evacuated Solar Tube Collectors (HP-ESTCs):

1. **Principles of Operation**: The researcher explains the fundamental principles underlying HP-ESTCs, which involve the utilization of heat pipes and evacuated tubes to efficiently capture and transfer solar energy. This may involve discussing how sunlight is absorbed by a selective coating inside the evacuated tubes, which then heats a working fluid (typically a refrigerant or water) contained within the heat pipes, leading to vaporization and subsequent heat transfer to a heat exchanger. Figure shows cross section of heat pipe



(a)

F2. ** selection of materials **: The various components of HP-ESTCs are outlined, including evacuated tubes, heat pipes, a condenser, a heat exchanger, insulation materials, and supporting structures. The function of each component and its role in the overall operation of the collector are discussed.

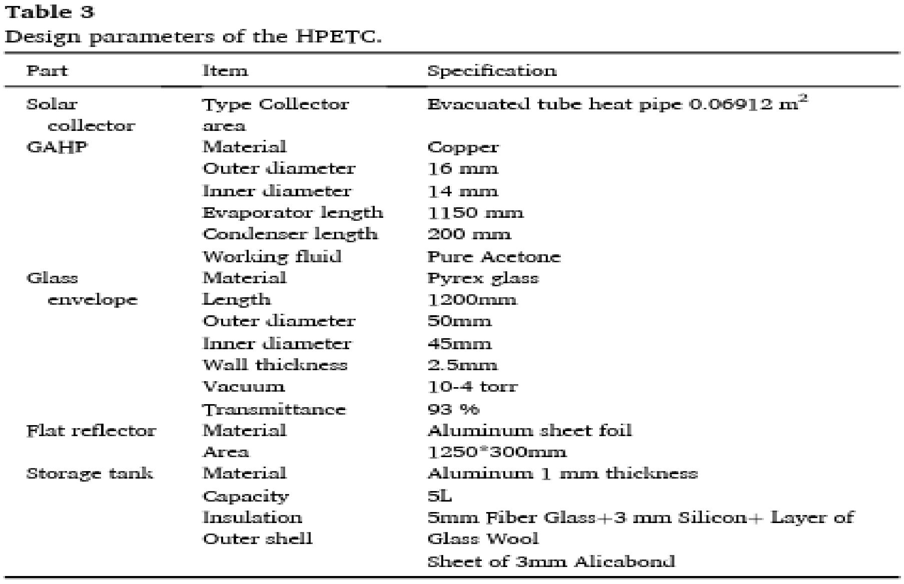


Table 3
Design parameters of the HPETC.

Part	Item	Specification
Solar collector	Type Collector area	Evacuated tube heat pipe 0.06912 m^2
GAHP	Material	Copper
	Outer diameter	16 mm
	Inner diameter	14 mm
	Evaporator length	1150 mm
	Condenser length	200 mm
	Working fluid	Pure Acetone
Glass envelope	Material	Pyrex glass
	Length	1200mm
	Outer diameter	50mm
	Inner diameter	45mm
	Wall thickness	2.5mm
	Vacuum	10-4 torr
	Transmittance	93 %
Flat reflector	Material	Aluminum sheet foil
	Area	1250*300mm
Storage tank	Material	Aluminum 1 mm thickness
	Capacity	5L
	Insulation	5mm Fiber Glass+3 mm Silicon+ Layer of Glass Wool
	Outer shell	Sheet of 3mm Alicabond

3. **Design Configurations**: Different design configurations of HP-ESTCs are explored, such as the number and arrangement of evacuated tubes, the type of heat pipe used, and the orientation of the collector relative to the sun. The advantages and limitations of each configuration may be discussed, as well as considerations for optimizing performance under different environmental conditions.

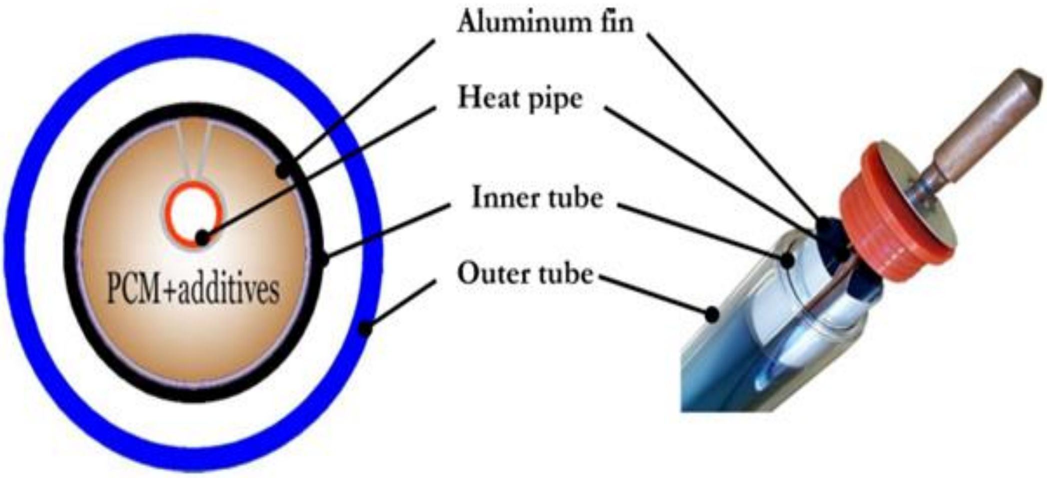


Fig. 2. The configuration of the used HPETC.

4. **Typical Applications**: The researcher highlights the diverse range of applications for HP-ESTCs, including domestic hot water heating, space heating, industrial process heat, and electricity generation through combined heat and power (CHP) systems. Case studies or examples of real-world installations may be provided to illustrate the practical utility of HP-ESTCs in various contexts.

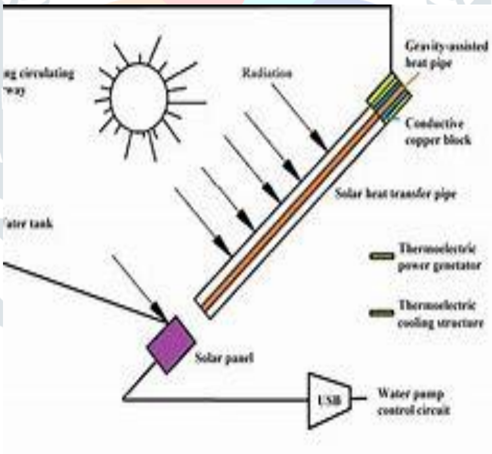
3.1 Heat Transfer Principles in HP-ESTCs:

In this subsection of the theoretical framework, the thesis delves into the fundamental principles of heat transfer that govern the operation of heat pipe evacuated solar tube collectors (HP-ESTCs). Here's a breakdown of what this section typically covers:

1. **Conduction**: The researcher explains how heats conducted through the various components of HP-ESTCs, including the absorber surface, the heat pipe, and the surrounding materials. This involves discussing the mechanisms by which heats transferred through solid materials and interfaces, such as lattice vibrations and electron diffusion.

2. **Convection**: The section explores the role of convection in HP-ESTCs, particularly in the context of heat transfer within the working fluid (typically a refrigerant or water) inside the heat pipe. This includes discussions on natural convection, forced convection, and mixed convection, as well as how these modes of heat transfer are influenced by factors such as fluid velocity, temperature gradients, and geometry.

3. **Radiation**: The researcher discusses the importance of radiation in solar energy absorption and heat transfer within HP-ESTCs. This involves explaining how solar radiations absorbed by the selective coating on the absorber surface of the evacuated tubes, as well as how thermal radiations emitted and exchanged between different components of the collector system.



4. **Selective Coatings**: The section may also touch upon the role of selective coatings in enhancing solar absorption and minimizing thermal radiation losses in HP-ESTCs. This includes discussions on the optical properties of selective coatings [6], such as their absorptivity, emissivity, and spectral selectivity, and how these properties affect overall collector performance.

By elucidating the principles of heat transfer in HP-ESTCs in this subsection, the researcher provides a theoretical foundation for understanding the mechanisms by which solar energy is absorbed, transferred, and utilized within the collector system. This knowledge is essential for developing mathematical models, computational simulations, and experimental analyses to evaluate and optimize the thermal performance of HP-ESTCs with thermal boosters in subsequent sections of the thesis.

Computational Analysis

Typically involves utilizing computational methods to analyse the performance of the integrated heat pipe evacuated solar tube collectors (HP-ESTCs) with thermal boosters. Here's a breakdown of what this section typically involves:

1. **Model Development**: The researcher begins by developing mathematical models or computational simulations of the integrated collector system with thermal boosters. This may involve using software tools such as MATLAB, ANSYS Fluent, COMSOL Multiphysics, or other computational fluid dynamics (CFD) software to simulate the fluid flow, heat transfer, and energy conversion processes within the collector system.

2. **Boundary Conditions**: The researcher specifies the boundary conditions for the computational analysis, including inputs such as solar irradiance levels, ambient temperatures, fluid flow rates, and material properties. These boundary conditions are based on real-world operating conditions and are essential for accurately simulating the performance of the collector system.

3. **Numerical Solution**: The thesis discusses the numerical solution techniques used to solve the governing equations of fluid flow, heat transfer, and energy conversion within the collector system. This may involve finite volume, finite element, or other numerical methods to discretize the equations and solve them iteratively to obtain numerical solutions.

4. **Parameter Sensitivity Analysis**: The researcher may conduct sensitivity analysis to assess the sensitivity of the computational model to variations in key parameters such as solar irradiance, ambient temperature, fluid flow rate, and thermal booster configuration. This helps identify critical parameters that influence collector performance and provides insights into system behaviour under different operating conditions.

5. **Validation**: The computational models validated against experimental data or analytical solutions to ensure it is accuracy and reliability. This involves comparing the numerical results obtained from the computational model with experimental measurements or theoretical predictions to assess agreement and identify any discrepancies or errors.

6. **Performance Evaluation**: The thesis evaluates the performance of the integrated collector system with thermal boosters based on the computational analysis. This includes calculating performance metrics such as thermal efficiency, energy capture efficiency, heat transfer rates, and temperature distributions within the collector system.

Experimental Validation

It is a crucial part of a thesis where the results obtained from experiments conducted earlier are analyzed, interpreted, and compared with theoretical predictions or numerical simulations. Here's a breakdown of what this section typically involves:

1. **Presentation of Experimental Results**: This section starts by presenting the experimental results obtained from the performance testing of the integrated heat pipe evacuated solar tube collectors (HP-ESTCs) with thermal boosters.t may include tables, graphs, charts, or other visual aids to effectively communicate the data collected during the experiments.

ii2. **Comparison with Theoretical Predictions or Numerical Simulations**: The experimental results are compared with theoretical predictions derived from mathematical models or numerical simulations conducted earlier in the thesis. This comparison allows the researcher to assess the agreement between experimental observations and theoretical expectations, identifying any discrepancies or areas where the theoretical model may need refinement.
3.**Evaluation of Performance Metrics**: The experimental data is analyzed to evaluate performance metrics such as thermal efficiency, energy capture efficiency, heat transfer rates, and temperature distributions within the collector system. This provides insights into the effectiveness of the thermal boosters in enhancing collector performance and improving energy capture and efficiency.

4. **Thermal performance calculation procedure**: The useful heat gained from the solar radiation by the flowing water can be calculated by:

$$Q_{us} = \dot{m}_w c_{pw} \Delta T_w$$

Where; ˙ mw is the water flow rate in (kg/s), cpw is the specific heat of water at constant pressure in (J/kg. ˚C), ΔTw is the temperature difference in (˚C) between outlet and inlet water.

Because the Phase change material has a latent and sensible heat, so if the PCM is integrated into the solar collector, the gained useful energy is divided into three parts depending on the phase of PCM: When a PCM is in a solid-state, the heat gain can be calculated by:

$$Q_{us} = \frac{m_{PCM} \cdot C_{P_s,PCM} \cdot \Delta T_{s,PCM}}{3600} \qquad (6)$$

Where

mPCM is the mass of PCM (kg), Cps, PCM is the solidstate specific heat of PCM (J/kg ˚C) and ΔTs, PCM is the temperature difference of the solid PCM.

The heat gains when the PCM undergoes a phase change process calculated by:

$$Q_{us} = \frac{m_{PCM} \cdot L_{PCM}}{3600} \qquad (7)$$

Where

LPCM is the latent heat for PCM in (J/kg). When a PCM is in a liquid phase,

the heat gain can be calculated by:

$$Q_{us} = \frac{m_{PCM} \cdot C_{p_{l,PCM}} \cdot \Delta T_{l,PCM}}{3600} \qquad (8)$$

Where

Cpl, PCM is the specific heat of PCM in the liquid phase (J/kg ˚C) and ΔTl, PCM is the temperature difference of the liquid PCM (˚C).

The daily efficiency of the reafference PCM-free collector can be calculated by:

$$(\eta_d)_{without\ PCM} = \frac{\dot{m}_w \cdot C_{pw} \cdot \Delta T_w}{\sum I \cdot A_{abs.} \cdot \tau_d} \qquad (9)$$

Where

I is the incident solar radiation (W/m2), Aabs. is the absorber area (m2) and ·τd is the transitivity.

The daily efficiency of the collector which equipped with pure or enhanced PCM can be estimated as [5]

$$(\eta_d)_{with\ PCM} = \frac{\dot{m}_w \cdot C_{pw} \cdot \Delta T_w \cdot dt}{\sum \left(I \cdot A_{abs.} \cdot \tau_d + \frac{m_{PCM} \cdot L_{PCM}}{3600} + \frac{m_{PCM} \cdot C_{pPCM} \cdot \Delta T_{PCM}}{3600} \right)} \qquad (10)$$

Where;

mw is the water flow rate in (kg/s), cpw is the specific heat of water at constant pressure in (J/kg.K), ΔTw is the temperature difference in (˚C) between outlet and inlet water, I is the incident solar radiation (W/m2), Aabs. is the absorber area (m2), τd is the transitivity, mPCM is the mass of PCM (kg), CpPCM is the specific heat of PCM at constant pressure (J/kg ˚C), LPCM is the latent heat for PCM in (J/kg), and ΔTPCM is the temperature difference of PCM (˚C).

While the evaporation and condensation heat transfer coefficients can be evaluated by [6]

$$h_{eva} = \frac{I}{\overline{T}_{eva)sur} - \overline{T}_{eva)core}} \tag{13}$$

$$h_{cond} = \frac{I(l_{eva}/l_{cond})}{\overline{T}_{cond)core} - \overline{T}_{cond)sur}} \tag{14}$$

Where

Teva) core and Tcond) core is the average core temperatures of the evaporator and condenser sections in (˚C) measured by five thermocouples located at various locations in the centre of GAHP as shown in Fig. 4, and lcond and leva are the condenser and evaporator lengths, respectively in (m).

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6. **Discussion of Uncertainties and Limitations**: The researcher acknowledges any uncertainties or limitations associated with the experimental validation, such as measurement errors, experimental variability, or limitations in the experimental setup.

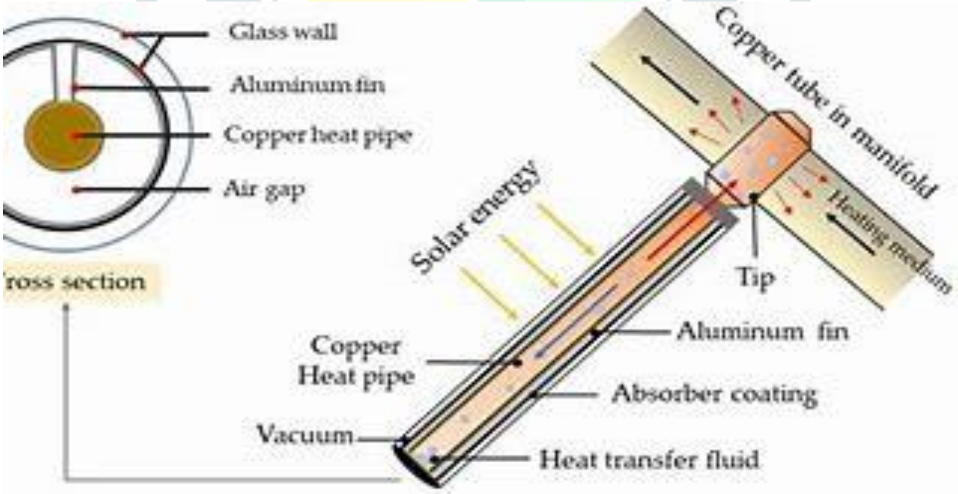
The standard deviation method was employed to perform the uncertainty calculations in this study

$$U_T = \sqrt{\varepsilon_r{}^2 + \varepsilon_s{}^2}$$

This ensures transparency and provides context for interpreting the experimental results.

6.1 presentation and analysis of the experimental setup

Its used for validating the performance of the integrated heat pipe evacuated solar tube collectors (HP-ESTCs) with thermal boosters. Here's a breakdown of what this section typically involves:



1. **Description of Experimental Setup**: This subsection begins with a comprehensive description of the experimental setup employed for performance testing.t provides details about the physical layout, dimensions, and components of the experimental rig, including the HP-ESTCs, thermal boosters, support structures, and any additional equipment used for data collection or control.

2. **Instrumentation**: The researcher discusses the instrumentation deployed in the experimental setup to measure relevant parameters during testing. The includes temperature sensors (e.g., thermocouples, resistance temperature detectors) for monitoring temperature profiles, flow meters for quantifying fluid flow rates, solar irradiance meters for measuring incident solar radiation, and any other sensors or data acquisition systems used for data collection.

3. **Calibration Procedures**: This subsection outlines the calibration procedures employed for the instrumentation to ensure accurate and reliable measurements.t describes how the sensors were calibrated against known standards or reference sources, the calibration intervals, and any adjustments made to improve measurement accuracy.

4. **Data Acquisition and Control**: The researcher explains the procedures for data acquisition and control during experimental testing. This includes details about data logging systems, sampling rates, and control strategies employed to maintain consistent testing conditions, such as temperature control systems or shading devices to regulate solar irradiance levels.

"Results and Discussion"

In the current research, three different flow rates (1, 2, and 3L/h) were tested experimentally in the proposed systems. Where Tests 1–3 are assigned for investigation of pure PCM, PCM enhanced with MP- ZnO, and PCM enhanced with NP-CuO integration in (ET) only at a mass flow rate of 1, 2, and 3 L/h respectively. Whereas Tests 4–6 were identified to investigate the integration of pure PCM, MP-ZnO-enhanced PCM, and NP-CuO-enhanced PCM within both (ET) and two separated storage tanks with a mass flow rate of 1, 2, and 3L/h respectively. The experimental details are listed in Table 5.

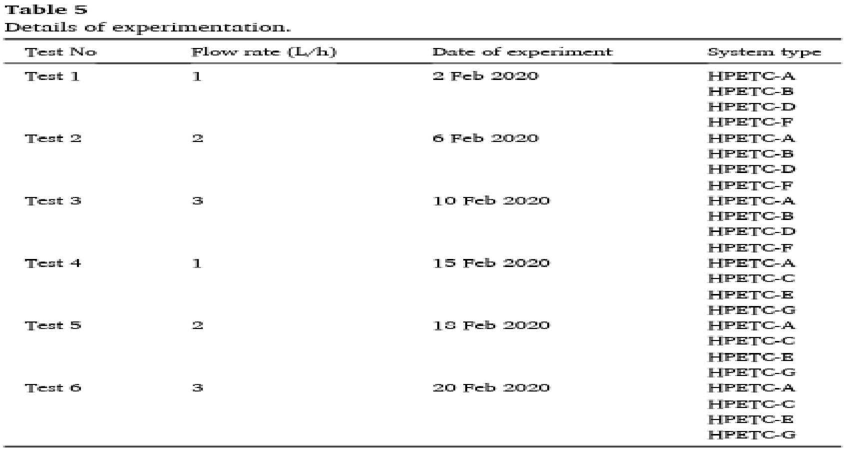
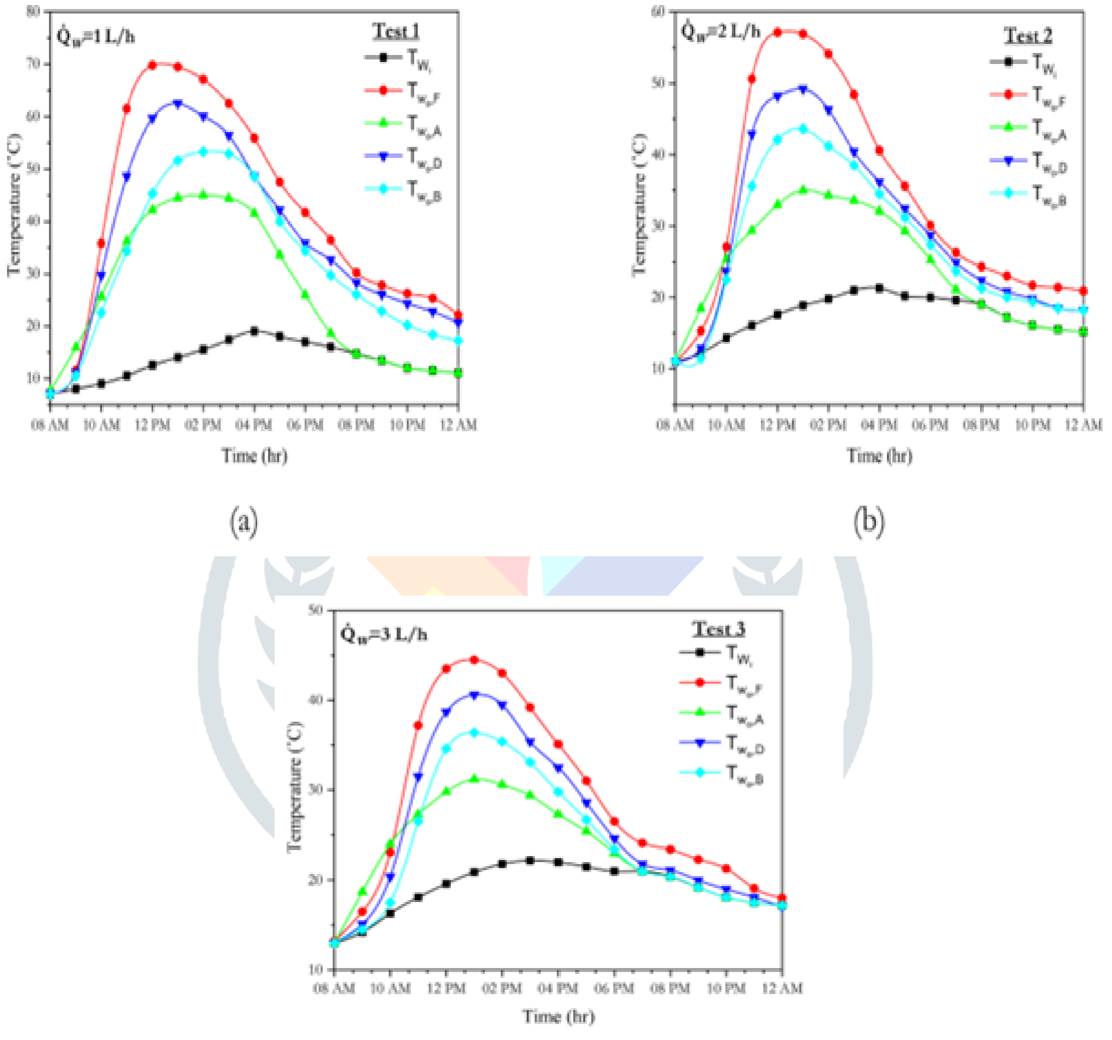


Table 5
Details of experimentation.

Test No	Flow rate (L/h)	Date of experiment	System type
Test 1	1	2 Feb 2020	HPETC-A HPETC-B HPETC-D HPETC-F
Test 2	2	6 Feb 2020	HPETC-A HPETC-B HPETC-D HPETC-F
Test 3	3	10 Feb 2020	HPETC-A HPETC-B HPETC-D HPETC-F
Test 4	1	15 Feb 2020	HPETC-A HPETC-C HPETC-E HPETC-G
Test 5	2	18 Feb 2020	HPETC-A HPETC-C HPETC-E HPETC-G
Test 6	3	20 Feb 2020	HPETC-A HPETC-C HPETC-E HPETC-G

7.1 Variation of inlet and outlet water temperature

In this section, the difference in outlet hot water temperature and inlet water temperature over time are discussed as illustrated in Figs. 7 and 8. Fig. 7(a), (b), and (c) presents the variation of outlet hot water temperature and inlet water temperature for Test 1–3 respectively. From Fig. 7, it is seen that the outlet hot water temperature highly depends on the water volume flow rate through the system. It was noticed that the system that used the enhanced paraffin with NP-CuO in its (ET) had a higher outlet hot water temperature as compared with the other systems. This is a result of the higher improvement in conductivity caused by the high thermal conductivity NP-CuO additives. Moreover, it was found that the system integrated with enhanced paraffin wax with MP-ZnO in its (ET) had a higher maximum water temperature than that with only pure paraffin wax.



(a) (b)

(c)

As shown in Fig. 7(a), at Test 1 with a water volume flow rate of 1 L/ h, the highest outlet hot water temperature for the HPETC-F (evacuated tube) about 69.8◦C , HPETC-D (evacuated tube) about 62.5◦C

HPETC-B (evacuated tube) about 53.3◦C , HPETC-A (simple tube) about 45◦C

The supplied hot water period from HPETC-F, HPETC-D, and HPETC-B were to be higher than HPETC-A

Fig. 7(b) and (c) shows the effect of increasing the water volume flow rate from 1L/h to 2 L/h and 3L/h respectively. At a flow rate of 2 L/h, the highest hot water temperature at the outlet of

HPETC-F 57.1◦C ,HPETC-D 49.2◦C ,HPETC-B 43.6◦C , HPETC-A 35.3◦C

While at a flow rate of 3 L/h, the highest hot water temperature at the outlet of

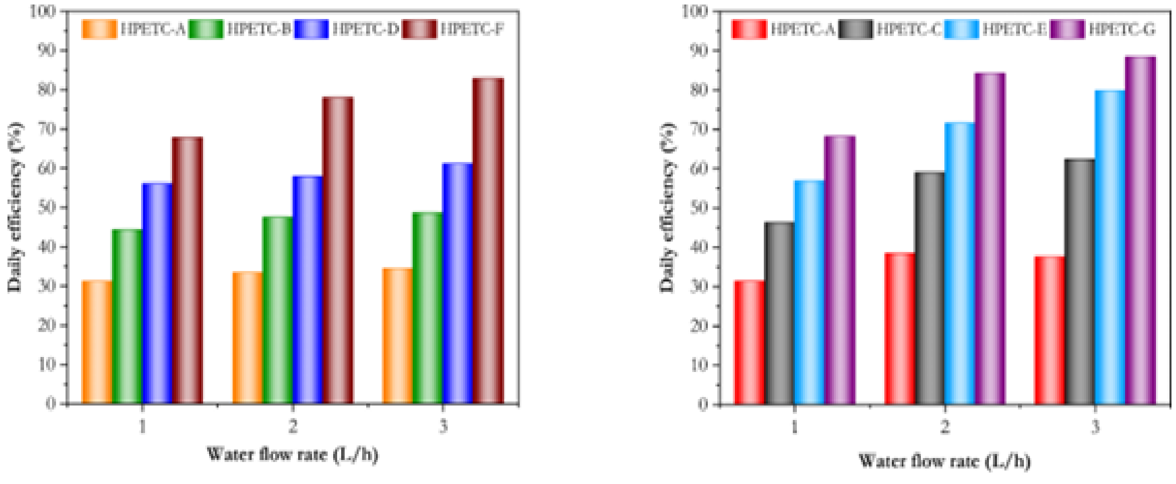
HPETC-F 44.5◦C ,HPETC-D 40.6◦C ,HPETC-B 36.4◦C , HPETC-A 31.2◦C

It was noticed that the system that used the enhanced paraffin with nano-CuO and micro Zn-O in its evacuated tube had a higher

1) outlet hot water temperature
2) improvement in conductivity

"Optimization and Efficiency Analysis,"

Based on the data obtained from the experiments, the daily thermal efficiency of each system was calculated by evaluating the gained useful energy as well as the incident solar radiation energy. Fig. 13(a) and (b) show the comparison of daily efficiency for Test 1–3 and Test 4–6 respectively. It is noted that the integration of PCM, regardless of the presence or absence of nano or micro-additives, leads to an improvement in the efficiency of the system compared to the reference free-PCM collector. This is because the integration of PCM into the solar collector extends the operating period of the collector by providing the system with thermal energy absorbed by PCM in times of absence of solar radiation at night or when the sky is overcast. Furthermore, the integration of PCM into (ET) decreases heat loss returns through the heat pipe in the absence of solar radiation at night.



(a) (b)

Fig. 13. The daily thermal efficiency at three various flow rates for (a) Test 1-3 (b) Test 4-6.

The addition of high thermal conductivity NP-CuO additives to paraffin wax is greatly affected the collector thermal efficiency. The reason is due to the acceleration of the thermal charging processes of the wax during the daytime by improving its thermal conductivity. Thereby increasing the amount of thermal energy gained by the system. It is also noticed that the use of MP-ZnO additives gives a relatively less improvement in collector efficiency. This is since the improvement of the thermal conductivity of the wax by using these additives is less than that in the case of NP-CuO additives. Fig. 13(a) presents the effect of using pure and enhanced paraffin wax integrated into only (ET) on the daily thermal efficiency through Test 1–3. It was observed that the maximum daily thermal efficiency was attained at Test 3 with a 3L/h water flow rate. Where the efficiencies of HPETC-F, HPETC-D, HPETC-B, and HPETC-A were 82.94%, 61.23%, 48.63%, and 34.5% respectively. As the water flow rate was 2L/h, Test 2 gave the second-highest daily efficiency of 78%, 57.9%, 47.6%, and 33.4% for HPETC-F, HPETC-D, HPETC-B, and HPETC-A respectively. While the lowest efficiency was obtained at Test 1 with the water flow rate of 1L/h, as the values of efficiencies were about 66.8%, 56.1%, 44.33%, and 32.23% for HPETC- F, HPETC-D, HPETC-B, and HPETC-A respectively.

CONCLUSION

This work presents the possibility of enhancing the functionality of a heat pipe evacuated tube collector (HPETC) by the integration of nano CuO or micro ZnO-enhanced paraffin wax as a thermal energy storage system (TESS) into one or both the evacuated tube (ET) and two separated storage tanks. So, three tests were conducted to investigate the integration of enhanced paraffin wax into only the (ET) with water flow rates (1, 2, and 3L/h). While another three tests with the same water flow rates were done to investigate the integration of enhanced paraffin wax into both the (ET) and two separated storage tanks. The following conclusions were obtained:

- Integrating pure or enhanced PCMs into both the (ET) and the two separated tanks significantly reduced the disadvantages of overheating heat pipe compared to the commercial PCM-free solar collector.

- By the improvement in the thermal conductivity of paraffin wax, the addition of (NP-CuO) and (MP-ZnO) reduced the melting time of the paraffin wax by about (1 and 0.5h), respectively.

- The addition of NP-CuO and MP-ZnO into the paraffin wax integrated into the (ET) only led to an increase in the supplied hot water period from the collector by about 5 and 6.2h, respectively higher than the PCM-free typical collector.

- The integration of the NP-CuO enhanced paraffin wax into the (ET) enhanced the evaporation and condensation heat transfer coefficients in the evaporator and condenser section, as these coefficients have the highest values of about 401 W/m 2 W/m 2 · ◦ C respectively with a flow rate of 1L/h. · ◦ C and 2366.4

- The integration of the MP-ZnO enhanced paraffin wax into the (ET) enhanced the evaporation and condensation heat transfer coefficients as the highest values were about 338.9 W/m 2 · 2136.4 W/m 2 · ◦ C respectively with a flow rate of 1L/h. ◦ C and

Future aspects

1. **Optimization of Particle Integration**: Future research could focus on optimizing the integration process of micro-ZnO and nano-CuO particles with paraffin wax within the solar collector system. This includes experimenting with different concentrations, particle sizes, and distribution methods to maximize thermal performance.

2. **Advanced Characterization Techniques**: Utilizing advanced characterization techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR) can provide deeper insights into the structural and chemical properties of the integrated particles and their interaction with paraffin wax. This can help in understanding the underlying mechanisms contributing to thermal enhancement.

3. **Long-Term Performance Evaluation**: Conducting long-term performance evaluations under various environmental conditions, including seasonal variations and extreme temperatures, can assess the durability, reliability, and stability of the integrated particle-paraffin wax system over time. This will provide valuable data for real-world applications and system longevity.

References

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