Solar Desalination Combined with Air Heater using Heat Pipe: Analytical Validation and ANSYS Simulation

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Abstract:
This study presents findings from experiments conducted using a heat pipe integrated with a solar still and air heater system. Sensible heat storage materials were introduced to enhance the heat storage capacity. Experiments were performed under different conditions, both with and without the heat pipe. The maximum recorded water temperature was 72°C when solar radiation of 1032 W/m² was applied, with a distillate output of 160 ml/h. Without the heat pipe, the water temperature achieved under the same solar input was lower, with a distillate output of 140 ml/h. The highest output of 240 ml/h was obtained when both heat pipes and sensible storage materials were used. An air temperature of 78°C was recorded when the heat pipe was utilized as the heat transfer medium. These results demonstrate the improved performance of the system when incorporating a heat pipe. A theoretical model was developed using Python, with further analysis carried out through ANSYS software.

Keywords: Air heater, Nanoparticles, Heat pipe, Desalination, Heat storage, Python, ANSYS.

1. Introduction

The availability of safe drinking water is critical for human survival, yet 97% of the earth's water is saline, and only a small percentage is freshwater. Desalination is the process used to separate salt from seawater, which requires energy—solar energy being an abundant and easily harnessed source. Hussain Akhtar, Arif Sayed Md, Aslam Md (2017)The paper titled "Emerging renewable and sustainable energy technologies: State of the art" appears in the journal Renewable and Sustainable Energy Reviews. It offers a comprehensive review of the advancements in renewable energy technologies, highlighting key sustainable practices and emerging technologies.Rajaseenivasan T, Srinivasan S, Srithar K (2015)This study, published in Energy, investigates solar air heaters, focusing on the use of circular and V-type turbulators on absorber plates. These turbulators are meant to enhance heat transfer efficiency within the solar air heater.Ekechukwu OV, Norton B (1999)In Energy Conversion and Management, this review covers various solar energy drying systems, with an emphasis on solar drying technologies. It presents an overview of the methods and types of solar dryers in use, exploring their effectiveness and applications.V.V Tyagi, N.L Panwar, N.A. Rahim, Richa Kothari (2012)This review, from Renewable and Sustainable Energy Reviews, focuses on solar air heating systems, both with and without thermal energy storage units. The paper evaluates the performance and efficiency of these systems in different settings.Alkilani Mahmud M, Sopian K, Alghoul MA, Sohif M, Ruslan MH (2011)Published in Renewable and Sustainable Energy Reviews, this paper reviews solar air collectors integrated with thermal storage units, summarizing the developments and efficiencies of different solar collector systems for better heat retention and use.Chamolia Sunil, Ranchan Chauhan, Thakur NS, Saini JS (2012)

This paper, also in Renewable and Sustainable Energy Reviews, reviews the performance of double-pass solar air heaters, which are designed to increase the heat transfer efficiency by allowing air to pass through the system twice.This paper aims to explore different designs and configurations of solar air heaters (SAHs). A dual-purpose still was fabricated, serving both desalination and air heating purposes, with two heat pipes used to enhance heat transfer. Various fluids, including nanofluids, were tested in the heat pipes.

2. Experimental Setup

A single-basin, single-slope solar still was fabricated using 1.4 mm thick steel, with a basin size of 0.81 x 0.75 x 0.7 m. The inside of the still was painted black to maximize heat absorption, and insulation was provided to minimize heat loss. The 4 mm thick glass cover was set at a 30° angle to the horizontal. The still was divided into two sections: one for solar distillation and the other for air heating.

A heat pipe, which uses phase transition to transfer heat, was placed inside the still. The working fluid in the heat pipe absorbs heat at the hot interface, vaporizes, and transfers heat to the cooler side, where it condenses and releases heat. This process repeats, allowing for highly efficient heat transfer. Nanofluids were also tested as working fluids in the heat pipes.

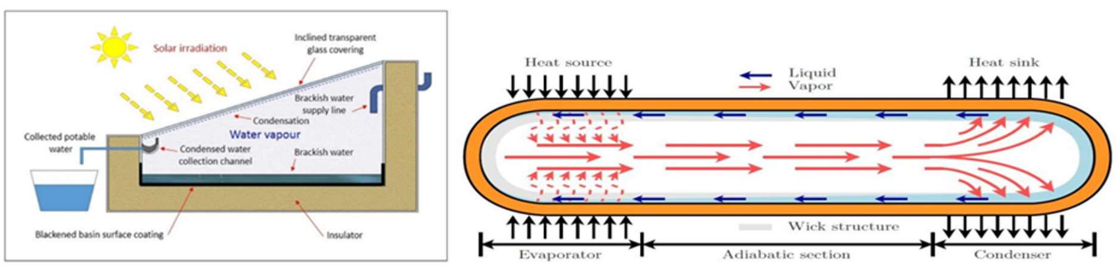

Fig.1 Experimental setup

3. Working Mechanism

Solar radiation is absorbed by the heat pipes positioned on both sides of the still, which transfer the heat to the water and air within the basin. The heated water undergoes desalination, and the condensate is collected at the bottom of the still. The heated air can be used for room heating or drying applications.

4. Modifications

In the modified setup, sensible heat storage materials were added to store heat for use during periods of low solar radiation. Initially, water was used as the working fluid in the heat pipes, but it was later replaced with nanofluids to test their performance.

5. Results and Discussion

i. Temperature Variation with Heat Pipe:

Figure 2 illustrates the increase in water temperature when the heat pipe is connected to the still. As solar radiation increases, so does the temperature of the fluid in the heat pipe, leading to a rise in water temperature, reaching a maximum of 68°C with solar radiation input of 1042 W/m². Air temperature reaches 72°C.

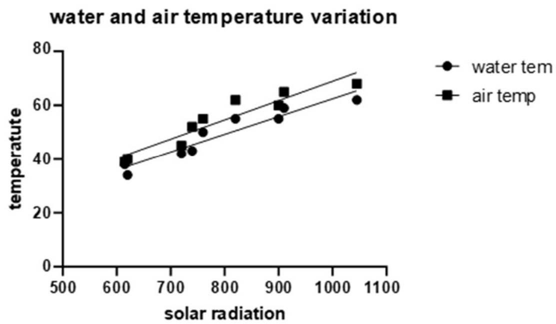

Fig.2 water and air temperature variation

ii. Effect of Heat Pipe Fluid on Temperature and Output:
Figure 3 shows that using nanofluids as the working fluid in the heat pipe results in improved performance compared to water. The use of nanoparticles led to a more significant temperature increase.

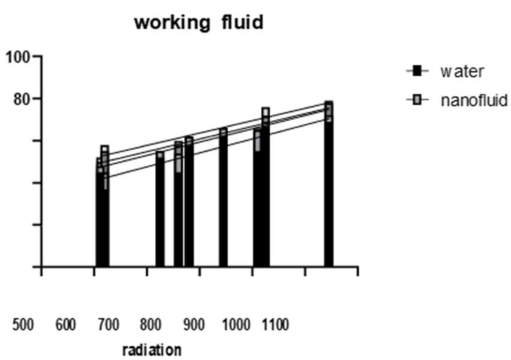

Fig.3 variation of nanofluid

iii. Temperature Variation without Heat Pipe:
Figure 4 highlights that without the heat pipe, the still's temperature is solely dependent on solar radiation. This results in a lower output of 140 ml/h under a solar radiation input of 924 W/m².

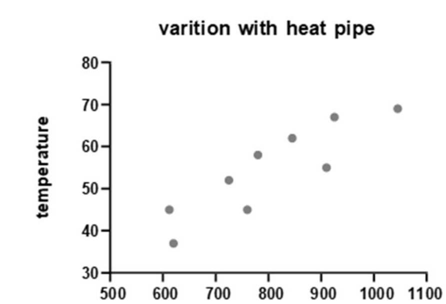

Fig.4 variation without heat pipe

iv. Temperature Variation with Heat Pipe and Sensible Materials:
Figure 5 shows that adding sensible storage materials, such as iron pieces and charcoal powder, improves heat retention, increasing the distillate output to 240 ml/h under solar radiation input of 924 W/m².

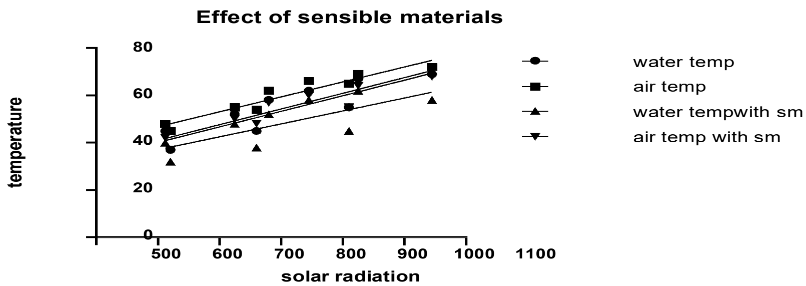

Figure 5 Heat Pipe and Sensible Materials

v. Temperature variation in heat pipe

simulation results from ANSYS related to temperature variation along a heat pipe. The left side of the image appears to depict a temperature profile in a heat exchanger or heat pipe, and the right side shows a cross-sectional view of the heat pipe, both demonstrating thermal gradients.From the description below the images, the text emphasizes the following key points:

- The **experimental values** are observed to be lower than the theoretical calculations.
- As heat is inputted at the evaporator section (the starting point of the pipe), the temperature rises, and this effect is more pronounced near the front end of the pipe. However, as we move along the length of the pipe toward the condenser end, the temperature decreases.
- The temperature variations in the simulation correspond with **experimental observations** and also match the expected **theoretical trends** in heat exchangers.
- The **turbulence effects** influence the heat transfer process, particularly due to velocity variations in the flow.
- The **numerical simulation** reveals that the temperatures at the evaporator end are higher than in the experimental setup, emphasizing that experimental values tend to be less than theoretical predictions due to factors like inefficiencies or external losses

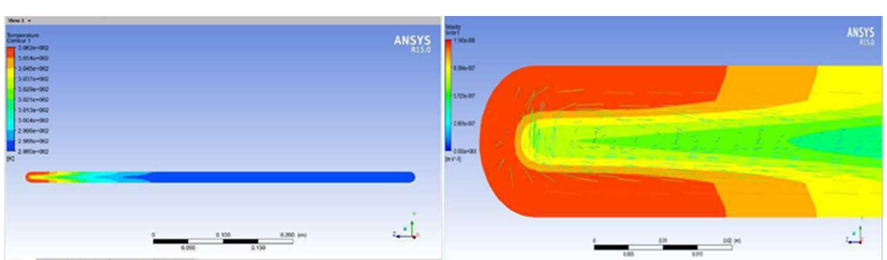

Fig.6 Temperature variation in heat pipe

vi.python program for heat pipe

heat pipe analysis - basic heat transfer calculation using Fourier's law

```
def heat_pipe_analysis(k, A, T_hot, T_cold, L):
    """  Calculate the heat transfer rate Q through a heat pipe.
    Parameters:
    k (float): Thermal conductivity of the pipe material (W/mK)
    A (float): Cross-sectional area of the pipe (m²)
    T_hot (float): Temperature at the hot end of the pipe (K)
    T_cold (float): Temperature at the cold end of the pipe (K)
    L (float): Length of the pipe (m)
    Returns:
    float: Heat transfer rate Q (Watts)
   """
    # Fourier's law of heat conduction
    Q = k * A * (T_hot - T_cold) / L
    return Q
# Example data for heat pipe
k = 200  # W/mK (example value for copper)
A = 0.01  # m² (cross-sectional area)
T_hot = 373  # K (hot side temperature, example)
T_cold = 293  # K (cold side temperature, example)
L = 1  # m (length of the pipe)
# Call the function
heat_transfer_rate = heat_pipe_analysis(k, A, T_hot, T_cold, L)
print(f"Heat Transfer Rate (Q): {heat_transfer_rate} W")
```

6. Conclusion

Incorporating a heat pipe into the solar still significantly enhances the system's performance. Sensible heat storage materials further improve heat retention and distillate output. Nanofluids, when used as the working fluid in the heat pipe, perform better than water. The theoretical model created using Python closely aligns with the simulation results from ANSYS, confirming the system's efficiency.

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