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Performance Analysis of a Horizontal Axis Spiral Type of Solar Collector Made of Copper Pipe on Solar Energy Absorption

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ABSTRACT

Renewable energy is a sustainable and inexhaustible energy source that can be obtained from water, wind, ocean waves, and solar radiation. Among them, solar energy is an abundant and underutilized resource. This study aims to investigate the heat transfer process from the evaporator pipe to the heated water and to analyze the performance of a horizontal-axis spiral-type solar collector. The results show that the collector effectively absorbs solar energy even under cloudy or rainy conditions, with the highest energy absorption of 35,700 J recorded between 12:00–13:00 WIB. Under cloudy weather, the maximum energy absorbed was 31,500 J between 15:00–17:00 WIB, while under hot conditions, the same energy value (31,500 J) was achieved between 11:00–17:00 WIB. This indicates that solar energy absorption largely depends on the temperature difference (ΔT) between the collector's inlet and outlet water temperatures.

KEYWORDS: *Solar energy, Solar collector, Spiral/coil.*

NOMENCLATURE

Q	Heat absorbed by water
m	Mass of water
Cp	Specific heat of water
ΔT	Temperature difference
Tin	Inlet water temperature
Tout:	Outlet water temperature
Tudara:	Ambient temperature

1. INTRODUCTION

Energy of demand for human has been continued to increase with population growth. Fossil fuels remain the most widely used energy source, but their availability is rapidly declining due to excessive use. One solution to reduce fossil fuel dependence is to utilize renewable energy sources. Solar energy, as one of the most abundant renewable sources, is widely utilized for heating through devices known as solar collectors. Various configurations of solar collectors, including flat-plate, evacuated-tube, and spiral/coil-type designs, have been developed to improve efficiency [1]. Recent developments in solar-based systems, such as solar panel tracking and control mechanisms, further demonstrate advancements in solar energy utilization [2]. Besides electricity generation, solar energy can also be used for heating purposes, such as water heating in homes, offices, hospitals, and hotels. Studies on thin-film photovoltaic and solar energy potential evaluation also highlight the growing interest in solar energy applications [3][4].

To maximize solar energy utilization for water heating, special devices called solar water heaters are required. These devices absorb and store thermal energy to heat water for domestic used, particularly for bathing. Hot water at temperatures between 27°C and 34°C is beneficial for human health, as it helps open skin pores, release toxins, relieve muscle pain, lower blood sugar, and reduce stress.

Based on these considerations, this study analyzes and tests a horizontal-axis spiral-type solar collector made of copper pipe repurposed from an evaporator coil, a configuration known to enhance heat absorption due to increased surface area and fluid residence time [5], to reduce the cost of water heating systems in residential, hospital, and hotel applications. Solar-based heating systems have been widely explored in various engineering applications, such as renewable-powered measurement devices [6] and solar thermal implementations in remote regions [7].

2. LITERATURE REVIEW

Heat transfer is a branch of thermodynamics that studies the process of heat energy flow caused by temperature differences between two or more media [8][9]. Applications related to heat exchangers, coiled-tube thermal devices, and solar-thermal technology continued to develop, supported by computational simulation approaches [10]. This phenomenon is commonly found in industrial systems, such as heat exchangers, coiled-tube thermal devices, and various heating applications that show improved thermal performance [11]. Naturally, heat flows from regions of higher temperature to regions of lower temperature until thermal equilibrium is reached. According to [12], the mechanisms of heat transfer can generally be classified into three types: conduction, convection, and radiation.

2.1 Heat Transfer of Conduction

According to Parabelem [12], heat transfer by conduction is a process in which heat flows from a region of higher temperature to a region of lower temperature within a single medium (solid, liquid, or gas) or between media that are in direct contact. In conductive heat transfer, the transfer of energy occurs through direct molecular interaction without significant movement of the molecules themselves.

According to kinetic theory, the temperature of a substance is proportional to the average kinetic energy of the molecules that constitute it. The energy possessed by an element of a substance, which is determined by the velocity and relative position of its molecules, is referred to as internal energy. Therefore, the faster the molecules move, the higher the temperature and internal energy of the substance. The molecules in one region have a greater average kinetic energy than those in an adjacent region as indicated by a temperature difference the higher-energy molecules transfer part of their energy to the molecules in the region with lower temperature.

This energy transfer may occur through elastic collisions, as in fluids, or through the diffusion of electrons moving rapidly from a high-temperature region to a lower-temperature region, as in metals. Regardless of the exact mechanism which is not yet fully understood the observable effect of heat conduction is the equalization of temperature. However, if the temperature difference is maintained by continuous addition and removal of heat at various points, a steady flow of heat will occur from the hotter region to the cooler one. Conduction is the only mechanism through which heat can flow within opaque solid materials.

2.2 Heat Transfer of Convection

Convection is the process of energy transport resulting from the combined effects of heat conduction, energy storage, and fluid motion. Convection plays a crucial role as a mechanism for both energy transfer and mixing motion. It is particularly important as a means of heat transfer between the surface of a solid body and a surrounding fluid, either liquid or gas. Energy transfer by convection from a surface at a temperature higher than that of the surrounding fluid occurs in several stages.

First, heat is conducted from the surface to the adjacent fluid particles. The energy transferred in this manner increases the temperature and internal energy of these fluid particles. The heated fluid particles then move toward regions of lower temperature within the fluid, where they mix and transfer part of their energy to other fluid particles. In this process, both the fluid and energy flow occur simultaneously. The energy is actually stored within the fluid particles and carried along as the bulk motion of the fluid.

This mechanism does not depend solely on temperature difference for its operation and therefore does not strictly meet the definition of heat transfer by conduction. However, since the net result is the transport of energy in the direction of the temperature gradient, it is categorized as a mode of heat transfer and referred to as heat transfer by convection.

2.3. Heat Transfer of Radiation

Radiation is the process by which heat flows from a body at a higher temperature to another body at a lower temperature when the two are separated in space, even if a vacuum exists between them. The term radiation is generally used to refer to all phenomena involving electromagnetic waves; however, in the study of heat transfer, it specifically refers to energy transfer caused by temperature differences that occurs through a transparent medium or across empty space. The energy transferred in this manner is known as radiant heat. Surface characteristics play a major role in radiation absorption, and absorber plates coated with black paint significantly improve thermal efficiency [13]. Radiation plays a major role in solar thermal systems, where absorber surface characteristics greatly influence performance. Recent investigations in optical and surface interactions, such as thin-film optical properties [3], support the understanding of radiation absorption mechanisms in solar collectors.

According to Parabelem [12], all bodies continuously emit radiant heat. The intensity of this emission depends on the body's temperature and surface characteristics. Radiant energy travels at the speed of light (3×10^8 m/s), and its behavior closely resembles that of visible light. Indeed, according to electromagnetic theory, light radiation and thermal radiation differ only in their wavelengths. Radiant heat is emitted by an object in the form of discrete packets of energy, known as quanta.

The propagation of radiant heat through space is similar to the propagation of light and can be explained using wave theory. When radiation waves encounter another object, the energy is absorbed near the surface of that object. Heat transfer by radiation becomes increasingly significant as the temperature of a body rises.

2.4. Convective Heat Transfer Concept

Convective heat transfer, as a mode of energy transfer, occurs in fluids as a result of the combined effects of conduction and the bulk motion of the fluid. The energy being transferred is the internal energy of the fluid. Convection also includes the transfer of latent heat associated with phase changes between the liquid and vapor states of the fluid. Considering the conditions of fluid flow, regardless of the specific mechanism of convective heat transfer, the rate of heat transfer can be expressed as follows [14]:

$$q'' = h\,A\,(T_s - T_\infty) \tag{1}$$

Where,

q'' = convection heat flux (W)
h = local convection coefficient or heat transfer coefficient (W/m²°C)
A = heat transfer area (m²)
T_s = wall temperature (°C)
T_∞ = ambient temperature (°C)

The heat transfer coefficient depends on the geometry of the surface, the nature of the fluid motion, and various thermodynamic and transport properties of the fluid. According to Rahmah [15], heat can be supplied to an object through a heating process, resulting in an increase in the object's temperature. Conversely, heat can be removed from an object through cooling, which leads to a decrease in its temperature. The amount of heat transferred can be calculated using the following equation [16]:

$$Q = m\,Cp\,\Delta T \tag{2}$$

where,

Q = total heat absorbed or released (J)
m = mass of an object (kg)
Cp= specific heat of a substance (J/kg°C)
ΔT= temperature change (°C)

3. METHODS

The initial stage of the research begins with determining the research topic and objectives. At this stage, the researcher identifies the problem to be addressed and formulates the hypotheses or specific goals to be achieved. The literature study stage involves collecting theories, concepts, and previous research findings related to heat transfer that was relevant to the research topic. This stage serves as the conceptual foundation and reference for designing the research methodology. It includes identifying reference sources such as books, journals, and scientific articles; developing a theoretical framework on conduction, convection, and radiation; and defining parameters such as environmental temperature and equipment specifications.

After establishing the theoretical foundation, the next step is preparing the tools and materials required for the experiment or testing. The tools used include grinders, welding equipment, measuring tools, and thermometers, while the materials used include insulators, evaporator pipes, aluminum foil, angle iron, temperature sensors, and black paint. This stage also involves selecting appropriate instruments according to the research requirements, performing calibration or functionality checks, arranging the equipment configuration, and ensuring all systems were ready for operation.

This study employed a theoretical modeling approach alongside an experimental investigation to comprehensively analyze the heat transfer process within the horizontal-axis spiral-type solar collector. The theoretical model based on the fundamental laws of thermodynamics and heat transfer, specifically addressing the three primary mechanisms: solar radiation absorption, conduction through the aluminum plate and copper coil walls, and convection between the plate/coil surface and the surrounding air, as well as between the copper coil wall and the flowing water. Key parameters to be determined include the collector efficiency, the overall heat loss coefficient and the useful heat gain.

The experimental setup for analyzing the horizontal-axis spiral solar collector involves the meticulous fabrication and assembly of the system's core components. The model utilized the specified dimensions of the aluminum plate (0.8 m x 0.4 m x 0.2 m) and material properties, considering the enhancement in absorptive due to the black paint coating. Appropriate energy balance equations formulated for the collector plate and the fluid within the copper coil**.**

A continuous copper coil attached to the back of the absorber plate in a spiral configuration, ensuring optimal thermal contact for efficient heat transfer to the water circulating within. This entire assembly was enclosed within an insulated casing and covered with a transparent glazing to minimize convective and radiative heat losses to the ambient environment, creating the complete solar collector unit. The collector then was mounted on a horizontal axis framework, allowing for minor adjustments in orientation to align with the sun, as required by the study's design.

The testing stage consists of conducting experiments in the field according to the established procedures, controlling variables that may affect the outcomes, and recording the conditions throughout the testing process. During the data collection stage, experimental results were systematically gathered by recording measurements and observations, repeating tests when necessary to obtain consistent data, and organizing the collected data into tables or graphs to facilitate analysis.

In the data analysis stage, the collected data were processed and analyzed to draw conclusions that align with the research objectives. Statistical methods or specific engineering analyses are applied, and the results are compared with theoretical expectations or findings from previous studies to interpret the outcomes accurately.

After analyzing the data, conclusions and recommendations are formulated to address the research problems and demonstrate the achievement of research goals. Recommendations may include suggestions for further studies, improvements in methodology, or practical applications of the findings. The final stage of the research process signifies that all phases from planning to report in a systematic and comprehensive manner.

4. RESULT AND DISCUSSION

This study discusses the heat transfer process in a horizontal-axis spiral-type solar collector. The heat transfer mechanisms involved include radiation, conduction, and convection. Solar radiation energy is absorbed by an aluminum plate of the collector (0.8 m × 0.4 m × 0.2 m), which was painted black to enhance heat absorption, and then transferred to a copper coil containing water.

The heat transfer from the plate to the fluid occurs through conduction and convection, producing hot water with a volume of approximately 0.5 liters per hour at a temperature range of 30–39°C, depending on weather conditions. The copper coil painted black enhances heat absorption due to its high thermal conductivity and emissivity, consistent with findings from blackened copper coil absorbers [17]. Solar energy performance is strongly influenced by weather conditions, and this principle is consistent with solar irradiance variability studies and PV potential evaluations [4]. Additionally, monitoring systems in solar-panel-based applications [2] demonstrate the importance of environmental conditions for solar system output stability. Experiment was conducted in three weather conditions: rainy, cloudy and sunny.

The experimental setup involved fabricating the spiral solar collector as described, including the black-painted aluminum absorber plate and the copper coil for water circulation. Instrumentation was installed to measure critical

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variables under controlled outdoor conditions. Figure 1 shows the horizontal axis solar collector tool used for the experiment, illustrating the arrangement of these components and their mounting for data collection. This visual aid allows readers to quickly understand the physical configuration being analyzed.

Figure 2: Horizontal axis solar collector

4.1. Condition of Rainy Weather

The temperature variation and heat performance result is shown in Figure 2. During the experimental measurements, the ambient temperature exhibited a relatively mild fluctuation, operating within a range of 22°C to 28°C. This moderate temperature range provided the baseline thermal environment for the collector's operation. The most significant indicator of the collector's performance was the temperature difference (ΔT) achieved between the water outlet and inlet, which reached its peak value of 17°C during the midday interval, specifically between 12:00 and 13:00 WIB. This peak (ΔT) signifies the time when the collector was operating at its maximum thermal efficiency, indicating the highest rate of energy transfer from the absorber plate to the circulating water. The heat value (useful heat gain) generated by the collector followed a characteristic parabolic pattern throughout the day. This pattern is directly correlated with the incident solar irradiance, which is typically highest around noon.

The heat value steadily increased from the morning hours, reaching a maximum recorded value of 35,700 J. simultaneously with the peak (ΔT) (between 12:00 and 13:00 WIB). Following this midday peak, the heat value began to decrease systematically toward the afternoon. This parabolic trend confirms the expected performance of a solar thermal collector, where heat gain is maximized when solar intensity is at its zenith and diminishes as the sun's angle lowers and the available solar energy decreases. Therefore, the ambient temperature ranged from 22°C to 28°C. The highest temperature difference (ΔT) of 17°C was recorded between 12:00 and 13:00 WIB, with a maximum heat value of 35,700 J. The heat value formed a parabolic pattern, increasing until midday and then decreasing toward the afternoon.

4.2. Condition of Cloudy Weather

The ambient temperature increased from 28°C to 30°C. The highest temperature difference (ΔT) of 15°C occurred between 15:00 and 17:00 WIB, with a maximum heat value of 31,500 J. The increase in water temperature and the amount of heat absorbed indicate that the collector's effectiveness improves with the intensity of solar radiation.

Figure 3: Heat received by water (Q) during rainy weather

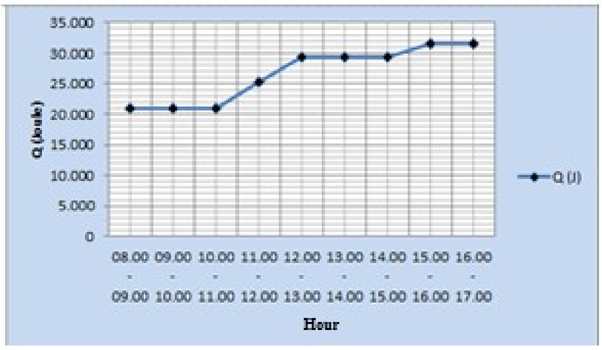

Figure 4: Heat received by water (q) during cloudy weather

The increase in water temperature and the amount of heat absorbed indicate that the collector's effectiveness improves with the intensity of solar radiation. This behavior aligns with previous studies showing that fluctuating solar irradiance under cloudy conditions directly impacts thermal [18].

4.3. Condition of Sunny Weather

The ambient temperature ranged from 28°C to 30°C, with the highest temperature difference (ΔT) of 15°C occurring between 11:00 and 17:00 WIB. The maximum heat reached 31,500 J, with stable water heating at an outlet temperature (Tout) of approximately 39°C. This condition indicates the optimal performance of the solar collector. Under sunny conditions, the collector reaches its optimal performance. Similar behaviour has been observed in solar-powered measurement systems [19] and in large-scale solar-based energy implementations [20], where peak output coincides with maximum sunlight availability.

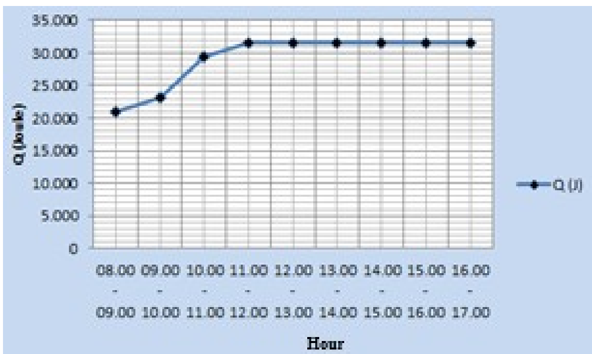

Figure 5: Heat received by water (Q) during hot weather

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Overall, the results show that the horizontal-axis spiral-type solar collector effectively absorbs solar energy and transfers it to the working fluid. The heat transfer efficiency increases with higher radiation intensity and ambient temperature, consistent with previously reported thermal behavior of coil-based solar heating systems [21]. Under cloudy conditions, energy absorption decreases significantly; however, the system remains capable of producing warm water, which aligns with findings that solar water heater performance remains functional despite variable irradiance levels [22]. This demonstrates the collector's consistent performance under various weather conditions, similar to earlier studies on blackened copper coil absorbers [18].

5. CONCLUSION

The heat transfer process from the evaporator pipe (a copper pipe in a spiral/coil shape) to the water occurs through convection, and the heat transfer to the spiral/coil copper pipe also takes place by convection. The ability of the horizontal-axis spiral-type solar collector to absorb solar energy under cloudy or rainy conditions reached its highest value of 35,700 J between 12:00 and 13:00 WIB, while under cloudy conditions, the maximum energy absorption of 31,500 J occurred between 15:00 and 17:00 WIB. Similarly, under sunny conditions, the collector was able to absorb solar energy of 31,500 J between 11:00 and 17:00 WIB. This indicates that greater solar energy absorption depends on the temperature difference (ΔT) between the inlet and outlet water of the collector.

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