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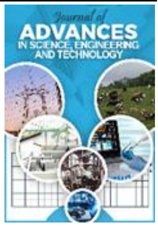

The Effect of Sunflower Oil and Water on Thermal Storage Parameters of a Flat Plate Solar Water Heating Collector

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ABSTRACT

Solar thermal energy conversion by flat solar collectors can be used for water heating to a temperature of 80°C. However, the thermal performance of these solar collectors is very much affected by varying weather conditions. Heat retention can effectively be achieved by the use of thermal storage fluids like sunflower oil. The aim of the study is to assess the effects of sunflower oil and water on the thermal storage capacity parameters of a flat plate solar water heater. Specific objectives were to determine the effect of water and sunflower oil on the peak output temperature, heat removal factor, heat loss coefficient, and efficiency of the flat plate solar water heating systems. Flat plate solar water heating collectors containing sunflower oil and water as thermal storage fluids were designed and constructed for this study. The absorber plate was made of mild steel welded to galvanized iron riser pipes. The temperatures were measured using K-type thermocouples connected to a data logger and a computer. Simulation and theoretical modeling were done using KOLEKTOR 2.2 software, while experimental data computation and analysis were done using MATLAB. Research findings showed that sunflower oil and air attained a peak temperature of 75°C, while that of water was 65°C from 12 noon to 3.30 pm. Sunflower oil has the longest stagnation (steady) temperature duration. Both experimental and theoretical results showed that sunflower oil has a higher removal factor F_R and efficiency factor F^1 than water. From the KOLEKTOR model, efficiency factor F^1 values of sunflower oil, water, and air are 0.922, 0.916, and 0.818, respectively. Sunflower oil is also a better thermal storage fluid than water since it has a lower heat loss coefficient than water. Other studies have also shown that sensible heat storage media improve efficiency by reducing thermal losses. The information from this study would be useful for the effective utilization of intermittent solar energy for heating applications. Thus, reducing water heating expenses and conserving our environment.

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1. Introduction

Solar thermal energy conversion for low-temperature applications, such as water heating, can be done by flat plate solar collectors with an absorber layer shown in Fig. 1. Solar water heaters normally undergo thermal losses due to varying weather conditions, such as incident solar radiation intensity, wind velocity, and ambient temperature. These conductive, convective, and radiative thermal losses reduce the output temperature and efficiency of solar thermal collectors. However, thermal energy storage within the solar collectors can be effectively achieved by using thermal storage fluids.

Sunflower oil has been reported to be a good heat transfer fluid (HTF) as well as a heat storage medium for domestic medium-temperature applications since it is readily available, non-corrosive, and food-grade (Mawire et al, 2015). The application of vegetable oils as sensible heat-storage materials has been encouraged (Hoffmann et al. 2018; Mawire et al, 2020; Mawire & Vanierschot, 2023).

There is inadequate information on the use of sunflower oil in terms of its heat loss coefficient and heat removal factor as a thermal storage fluid in solar water heaters. However, these parameters greatly affect the thermal performance of solar water heating

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systems. This paper's discussion focuses on comparing the effectiveness of sunflower oil and water as both heat transfer and thermal storage media on the thermal performance of a typical solar water heating system.

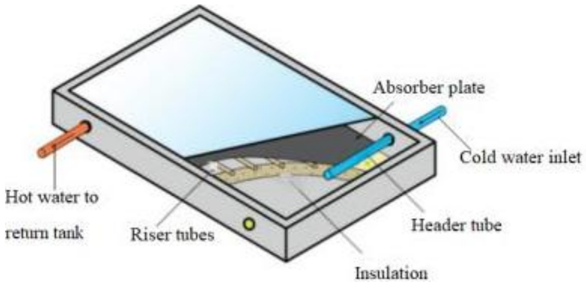

Fig. 1: Absorber layer made of metallic tubes (Foster et al, 2010)

1.1. Solar Collector Thermal Performance and Storage Parameters

The daily hot water energy demand (L) can be determined from Eq. 1, where L is the daily hot water energy demand ($kWh\, day^{-1}$), V is the volume of water per day ($m^3\, day^{-1}$), ρ density of water, c is the specific heat capacity of water, T_{hot} is the water delivery temperature, and T_{cold} is water temperature.

$$L = V\rho c(T_{hot} - T_{cold}) \tag{1}$$

The collector area (A_c) suitable for the hot water daily demand can be determined by Eq. 2, where L is the daily hot water energy demand, F_{solar} is the solar fraction (which is 60% minimum for Kenya), η_{solar} is solar system efficiency (usually 40%), I_{av} is average daily solar irradiance ($kWh\, m^{-2}day^{-1}$) (Warui et al, 2017).

$$A_c = \frac{LF_{solar}}{\eta_{solar}I_{av}} \tag{2}$$

Sizing a solar water heater, therefore, greatly depends on solar radiation intensity to achieve the desired fluid temperature. The radiant flux striking the plate is computed according to Eq. 3, where I_T is the irradiance on the collector, A_P is the plate's exposed area and τ_{cov} is the transmittance of any transparent cover.

$$I = \tau_{cov}A_P I_T \tag{3}$$

The rate of thermal energy loss from the plate to the environment (Q_L) is given Eq. 4, where, R_L is the resistance to thermal energy loss from the T_p and T_a are the plate and outside temperatures, respectively.

$$Q_L = \frac{T_p - T_a}{R_L} \tag{4}$$

The net thermal energy flow into the plate is given by Eq. 5, where, α_p is the plate absorbance, η_{sp} is the capture efficiency < 1 and $U = \frac{1}{R_L A_P}$ is the overall heat loss coefficient. The first two forms of Eq. 5 is referred to as the Hottel-Whillier-Bliss equation.

$$\left.\begin{aligned} P_{net} &= \tau_{cov}A_p I_T - \frac{T_p - T_a}{R_L} \\ P_{net} &= A_P\{\tau_{cov}\alpha_p I_T - U(T_p - T_a)\} \\ P_{net} &= \eta_{sp}A_p I_T \end{aligned}\right\} \tag{5}$$

The total plate-to-glass resistance to heat loss (R_{pg}) is given by Eq. 6, where R_{vpg} and R_{rpg} are convective and radiative heat loss resistances between the plate and glass, respectively (Twidel & Weir, 2006).

$$R_{pg} = \left(\frac{1}{R_{vpg}} + \frac{1}{R_{rpg}}\right)^{-1} \tag{6}$$

The energy gained by the receiver Q_r at any instant is given by Eq. 7, where $(\tau\alpha)_{eff}$ is the effective transmittance-absorbance product. I_T is the incident solar radiation on the tilted collector, and AC is the aperture area of the collector.

$$Q_r = (\tau\alpha)_{eff}I_T A_C \tag{7}$$

The glazing on the solar collector confines long-wavelength infrared radiation within the collector. The convective heat loss, Q_{conv} to the surrounding expressed in Eq. 8 is caused by the temperature difference between the plate and the ambient.

$$Q_{conv} = UA_r(T_r - T_a) \tag{8}$$

Where A_r is the receiver area, U is an overall heat loss coefficient, T_r is the receiver's temperature and T_a is the ambient temperature. Radiative heat loss due to the temperature difference between the receiver and sky dome is expressed according to Eq. 9, where ε_{eff} is the effective emissivity of the collector, and σ is the Stefan-Boltzmann constant.

$$Q_{rad} = \varepsilon_{eff}\sigma A_r({T_r}^4 - {T_a}^4) \tag{9}$$

Thermal losses from the bottom and edges of the collector are assumed since their contributions are insignificant compared with convective and radiative losses. The collector energy balance equation, therefore, combines the receiver heat gain expressed in Eq. 7 and the accompanying convective and radiative heat losses expressed in Eqs. 7 and 8 is given in Eq. 10, where Q_u is the usable collected energy.

$$\begin{aligned} Q_u = (\tau\alpha)_{eff}I_T A_C - UA_r(T_r - T_a) \\ - \varepsilon_{eff}\sigma A_r({T_r}^4 - {T_a}^4) \end{aligned} \tag{10}$$

The instantaneous thermal efficiency relates the usable collected energy and incident solar energy according to Eq. 11, while the overall efficiency within a given period of time is expressed in Eq. 11.

Radiative heat losses are very minimal in low temperature collectors, such as flat plate collectors, as compared with convective losses. Hence, its efficiency is simplified according to Eq. 13.

$$\eta = \frac{Q_u}{I_T A_C} = (\tau\alpha)_{eff} - \frac{UA_r}{I_T A_C}(T_r - T_a) - \frac{\varepsilon_{eff}\sigma}{(I_T A_C)(T_r{}^4 - T_a{}^4)} \quad (11)$$

$$\eta = \frac{\int_{t1}^{t2} Q_u dt}{A_C \int_{t1}^{t2} I_T dt} \quad (12)$$

$$\eta = \frac{Q_u}{I_T A_C} = (\tau\alpha)_{eff} - \frac{UA_r}{I_T A_C}(T_r - T_a) \quad (13)$$

The collector heat removal factor F_R relates the collector's actual useful thermal energy gain to the useful gain if the overall collector surface were at the fluid inlet temperature. Thus, the efficiency and the useful heat gain Q_u are expressed according to Eq. 14 and Eq. 15, respectively.

$$\eta = F_R\left\{(\tau\alpha)_{eff} - \frac{UA_r}{I_T A_C}(T_{in} - T_a)\right\} \quad (14)$$

$$Q_u = \eta I_T A_C = I_T A_C F_R\left\{(\tau\alpha)_{eff} - \frac{UA_r}{I_T A_C}(T_{in} - T_a)\right\} \quad (15)$$

The usable heat gained by the working fluid can also be expressed as a function of both the inlet T_{in} and outlet T_{out} as given in Eq. 16, where, c_p and $\dot{m}$ are the specific heat capacity at constant pressure, and mass flow rate of the working fluid, respectively (Shariah 1991; Santiago & Jimenez, 2002; Duffie & Beckham, 2006; Struckmann, 2008; Fraisse et al. 2007; Fabio, 2013; Garg et al. 2013).

$$Q_u = \dot{m}c_p(T_{out} - T_{in}) \quad (16)$$

Therefore, the Heat removal factor can be expressed in the form given in Eq. 17 (Santiago & Jimenez, 2002; Baldini et al. 2009; Daghigh et al, 2011)

$$F_R \frac{\dot{m}c_p(T_{out} - T_{in})}{I_T A_C\left\{(\tau\alpha)_{eff} - \frac{UA_r}{I_T A_C}(T_{in} - T_a)\right\}} \quad (17)$$

There are three test methods used in assessing the thermal performance of a flat plate solar water heater. These methods are: collector time constant (τ) test, instantaneous thermal efficiency (η) test, and incident angle modifier $K\theta_b(\theta)$. The τ-test is used by setting the environmental conditions to standard requirements, where variation in irradiance and ambient temperature must be within $\pm 32\, W\, m^{-2}$ and $\pm 1.5\, K$, respectively, (Rojas et al. 2008).

The ASHRAE 93 standard test is an outdoor steady-state thermal method conducted under suitable weather conditions. This method requires very narrow ranges of irradiance, temperature, and wind speed. The conditions for this test are a minimum isolation of $790\, W\, m^{-2}$, a maximum diffuse fraction of 20%, wind speed between 2.2 and $4.5\, m\, s^{-2}$, and an incidence angle modifier between 98 and 102% (normal incidence value). This test method cannot be universally used since such environmentally prescribed conditions cannot be obtained in some locations (ENI93-2003). A more reliable method is the transient EN12975-2 test since it can be carried out over a larger range of environmental conditions (EN12975-2:2001). The incidence angle modifier $K\theta_b(\theta)$ test involves fixing one inlet temperature at steady-state conditions throughout the whole test to determine the collector efficiency at the incidence angles of 0, 30, 45, and 60^0 by means of a second-order equation. Varying the azimuth angle of the collector shifts the incidence angles (ISO Standard 1908-E, 1994; Walker, 2013).

The angular dependence of the incidence angle modifier upon the incidence angle θ is approximately given by Eq. 18.

$$K\theta_b(\theta) = 1 - b_o\left[\frac{1}{\cos\theta} - 1\right] \quad (18)$$

The parameter b_o is known as the incidence angle modifier coefficient. The effect of the modifier angle on the efficiency is then given by Eq. 19, where η_n is the efficiency value for normal incidence when there are no optical losses through the gap between the receiver and the reflector.

$$\eta = \eta_n\left\{1 - b_o\left[\frac{1}{\cos\theta} - 1\right]\right\} \quad (19)$$

Hence, the collector efficiency and the incidence angle modifier are generally expressed by the second-order Eqs. 20 and 21, where a_o is the intercept of the performance curve, a_1 and b_o are the first-order coefficients for the respective equations, and a_2 and b_1 are the second-order coefficients (Foster et al. 2010).

$$\eta = a_o K\theta_b(\theta) - a_1 \frac{T_{in} - T_a}{I_T}{}_1 - a_2\frac{(T_{in} - T_a)^2}{I_T} \quad (20)$$

$$K\theta_b(\theta) = 1 - b_o\left[\frac{1}{\cos\theta} - 1\right] - b_1\left[\frac{1}{\cos\theta} - 1\right]^2 \quad (21)$$

Fig. 2: Layout of flat plate solar water heating system

Heat loss can be expressed by Eq. 22 (Andoh et al. 2010) and thermal conductivity is expressed by Eq. 23, where q is the heat current, k the thermal conductivity, A the cross-sectional area of the heat flow, and $\frac{dT}{dx}$ the temperature gradient (Adrian & Kran, 2003; Theodore et al. 2007).

$$Q_L = A_C U(T_{abs} - T_a) \quad (22)$$

From the literature review, it is important to note that the effects of sunflower oil and water on heat loss coefficient, heat removal factor, and efficiency, as thermal performance parameters of flat plate solar water heaters, have not been adequately investigated, hence the main focus of this paper.

$$q = -kA\frac{dT}{dx} \tag{23}$$

2. METHODOLOGY

3.1 Experimental Work

2.1.1. Designing a Flat Plate Solar Water Heating System

The prototype water heating system, which consists of a water supply tank, a flat plate solar collector, and a hot water storage tank, was constructed as shown in Fig. 2. The hot water storage unit was insulated using styrofoam.

In this study, three flat plate solar water heaters containing water and sunflower oil and air as thermal storage fluids were designed with the following parameters:

Collector Box Parameters

The flat plate solar collector box of the following specifications was built:

- The collector has gross dimensions of 127 cm long, 98cm wide, and 7 cm deep, with a 20° slope.
- The collector box interior surface is made of a metallic sheet with a wood of thickness 2.5 cm as an insulating material.
- The collector has a liquid volume capacity of 30 liters.
- The collector's external surface was protected by an aluminum-painted metallic sheet.
- A transparent glass glazing of 4mm thickness is used to cover the collector box.

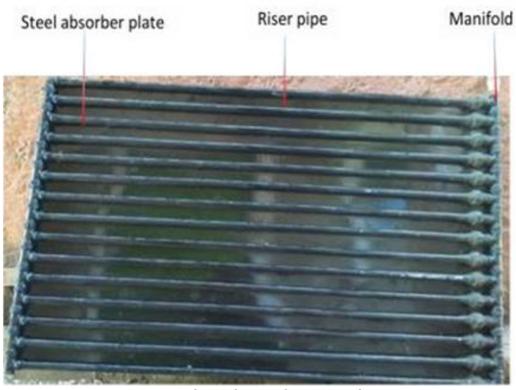

Fig. 3: Absorber plate with pipes

Absorber Parameters

A Steel absorber plate was welded on 15 GI riser pipes, each 118 cm long and spaced at 5 cm intervals. The absorber-frame gap and absorber-glazing gap were 2 cm each. The absorber plate and tubes were assembled and joined as shown in Fig. 3.

The pipes welded on the absorber plate were immersed in sunflower oil and water, which are thermal storage fluids. Both experimental and theoretical results were obtained from computational data analysis from MATLAB and the KOLEKTOR 2.2 model, respectively.

3. Results and Discussions

The thermal performance assessment of a flat-plate collector can be conducted by applying the fundamental laws of thermodynamics and relationships from heat transfer and fluid mechanics. Thermal performance analysis of the solar water heater discussed in this paper considered the following parameters: output fluid temperature, collector efficiency, overall heat loss coefficient U, heat removal factor F_R, and efficiency factor F_I. Some of these thermal performance parameters can be determined from the "Hottel-Whillier-Bliss" efficiency curve.

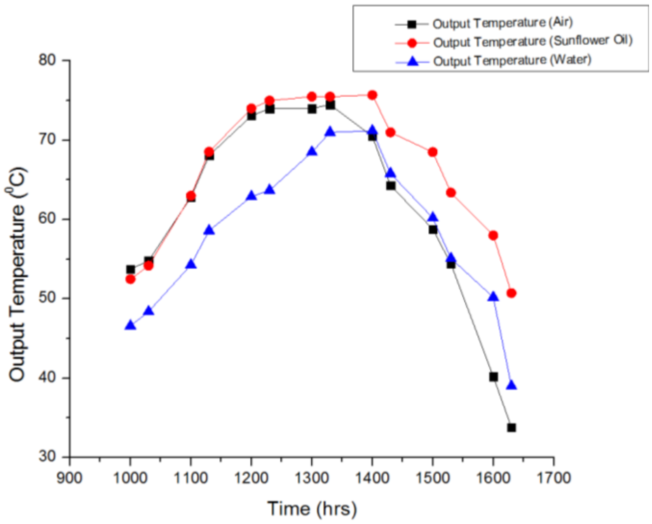

Fig. 4: Experimental peak water outlet temperatures due to thermal storage fluids.

3.2 Peak Output Temperature

The output temperature of a solar heating system is greatly affected by solar radiation intensity and ambient temperature, which are dependent on varying weather conditions. The output temperature also depends on the following thermo-physical properties of the sensible heat storage medium: specific heat capacity and thermal conductivity. The performance of air, water, and sunflower oil as thermal energy storage (TES) fluids in a flat plate solar water collector was comparatively analyzed. Their output temperatures increased with incident solar intensity from morning up to 1400hrs, then dropped from 1430hrs as shown both in the experimental and theoretical graphs in Fig. 4 and Fig. 5, respectively.

The peak output temperature attained by the experimental flat plate solar water heater with sunflower oil as TSF was 75.7 ℃. However, the peak output temperatures for water and air were 71.2 ℃ and 74.0 ℃, respectively. It is also important to note that the rates of thermal energy gain and energy loss are faster in air than in water as thermal storage fluids in solar water heaters. The low output temperature for water as a sensible heat storage fluid is due to its high specific heat capacity as compared to other fluids. The rate of heat loss in sunflower oil as a thermal storage medium was much lower than in water. For instance, at 1600hr, the storage fluid output temperatures for sunflower oil, water, and air were 58.0℃, 50.2℃, and 40.2℃, respectively. Thus, sunflower oil is a better thermal storage fluid than water and air. Experimental and theoretical results on the peak output temperature agree despite experimental errors.

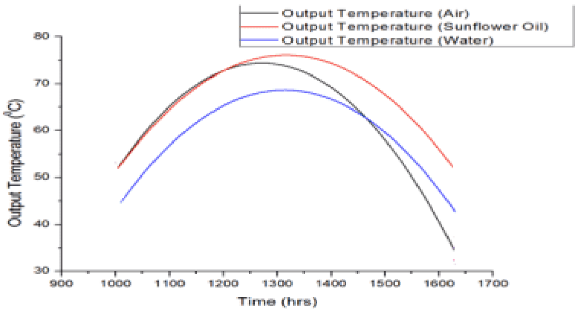

Fig. 5: Theoretical peak water outlet temperatures due to thermal storage fluids

The maximum temperature rise in comparison with the inlet water temperature of the flat plate solar water heater due to air, sunflower oil, and water as thermal storage media is 45.5 ℃, 46.5 ℃, and 42.0 ℃, respectively. The low-temperature increase due to water as a thermal storage fluid is due to its high thermal energy absorption since it has a high specific heat capacity. The thermal losses associated with air, water, and sunflower oil as thermal storage media were investigated both experimentally and theoretically. The research findings were presented in the graphs shown in Fig. 6 and Fig. 7, respectively.

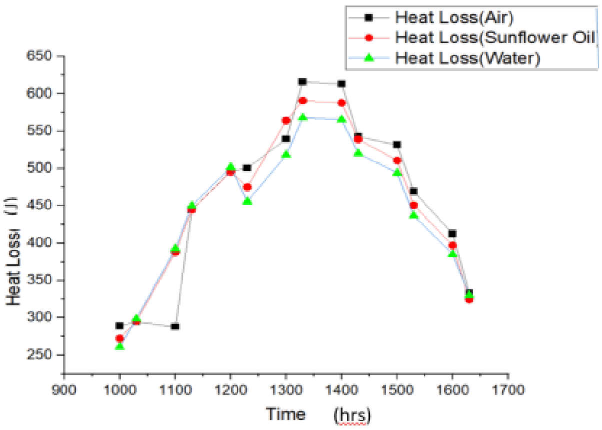

Fig. 6: Experimental Instantaneous thermal losses within solar collectors associated with air, sunflower oil, and water as thermal storage media.

The heat loss in water is less compared to sunflower oil, even though the collector output temperature due to sunflower oil is greater than that of water as thermal storage media. The higher thermal loss due to sunflower oil occurs since it has a higher thermal conductivity than water. Both experimental and theoretical results show that thermal storage media minimize heat losses. This has been supported by other studies on the effectiveness of thermal storage media in solar collectors.

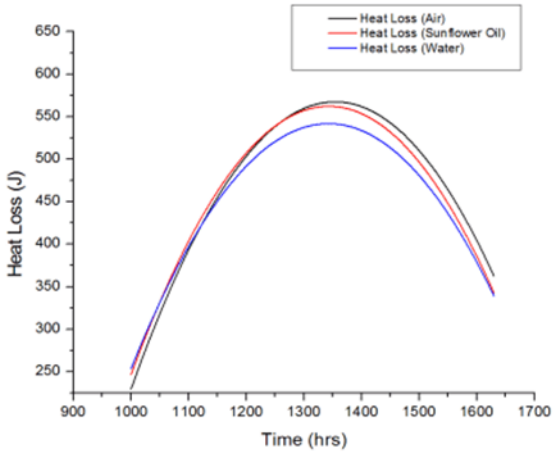

Fig. 7: Theoretical Instantaneous thermal losses within solar collectors associated with air, sunflower oil, and water as thermal storage media

3.3 The flat plate solar water heater efficiency

Solar-thermal energy conversion performance of a solar water heating system is based on its output fluid temperature, which determines its efficiency. The amount of energy absorbed by the working fluid is a portion of the useful energy collected after the thermal losses. The experimental and theoretical instantaneous efficiency curves for the thermal storage fluids from 1000hrs to 1600hrs are shown in Fig. 8.

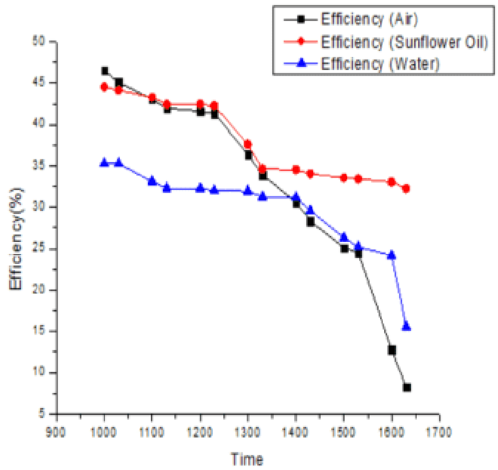

Fig. 8: The experimental instantaneous efficiency curves for the thermal storage fluids

The theoretical instantaneous efficiency curves computed from the KOLEKTOR 2.2 model results are shown in Fig. 9. The efficiency trend curves from experimental and theoretical results indicate a general efficiency decline of the flat plate solar water heating system from morning to evening. The instantaneous drop in the solar water heater efficiency is minimized by the use of thermal storage fluid. Thus, sunflower oil has a higher efficiency than water in solar thermal storage in a flat plate solar water heating system. This result is in agreement with earlier studies that sensible heat storage media reduce heat losses and increase efficiency (Piyush et al.2022). Sunflower oil in particular, under low and high power charging, has energy storage efficiency of 85% and 78% respectively (Mawire et al.2014).

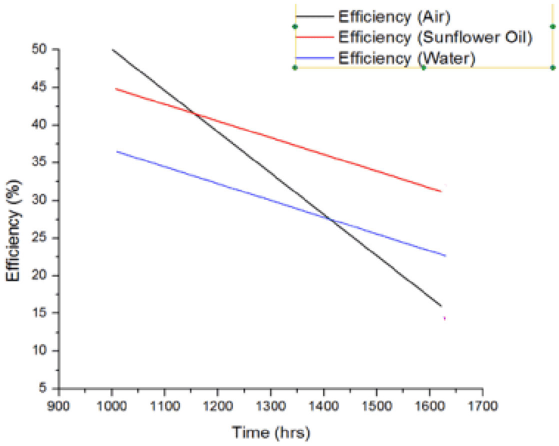

Fig. 9: Theoretical instantaneous efficiency curves for the thermal storage fluids

3.1. Collector Heat Loss Coefficient and Heat Removal Factor

The experimental and theoretical efficiency curves derived from the "Hottel-Whillier-Bliss equation" (Foster et al,2010), which can be used to determine heat loss coefficient and heat removal factor for the solar water heaters, are shown in Fig. 10 and Fig. 11, respectively.

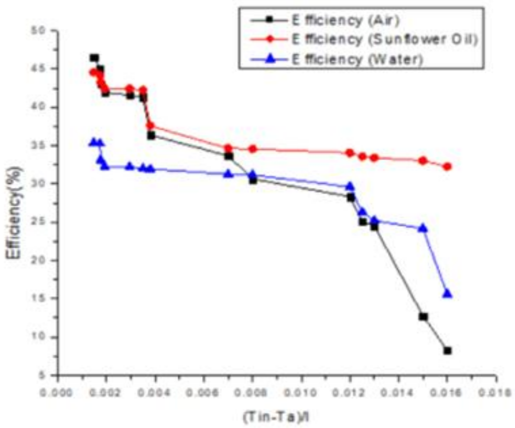

Fig. 10: Experimental overall collector efficiency curve.

The research findings showed the overall heat loss coefficients U for air, water, and sunflower oil as $-38.40\ W\ m^{-2}K$, $-20.94\ W\ m^{-2}K$ and $-15.80\ W\ m^{-2}K$, respectively. The effective transmittance-absorbance product of the solar collector system was 0.874.

The collector heat removal factor FR, defined as the ratio of the actual heat transfer to the maximum possible heat transfer, can therefore be compared to the effectiveness of a conventional heat exchanger (Matuska & Zmrhal, 2009). From the experimental results, our solar water heater has a heat removal factor FR of 0.7330, 0.7391, and 0.6152 for air, sunflower oil, and water, respectively. However, from the KOLEKTOR 2.2 model, the heat removal factor F_R for sunflower oil is 0.937, while water and air have heat removal factors of 0.918 and 0.910, respectively. Both experimental and theoretical results showed that sunflower oil has the highest heat removal factor; hence, sunflower oil is effective for the heat exchange mechanism.

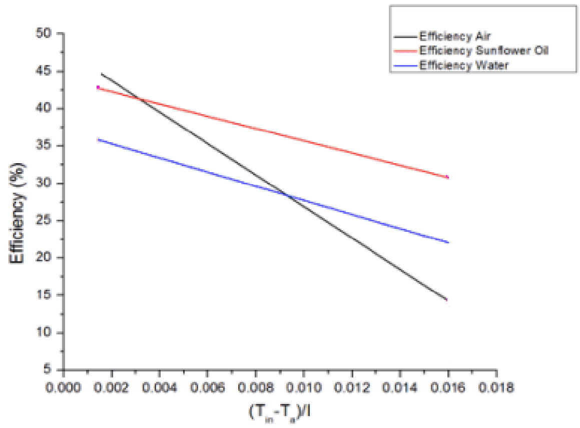

Fig. 11: Theoretical Overall Collector Efficiency Curve.

The usable thermal power output from the collector, based on the mean fluid temperature, is assessed from the efficiency factor F_I. This parameter describes how efficiently heat is transferred from the absorber surface to the heat transfer fluid. From the KOLEKTOR 2.2 model efficiency factor F_I values of sunflower oil, water, and air are 0.922, 0.916, and 0.818, respectively. These research findings show that sunflower oil is a better heat transfer fluid than both water and air. It has been reported that sunflower oil is suitable for high-temperature charging during thermal storage, leading to high energy, high exergy, and exergy factor (Mawire et al.2015).

It is worth noting that experimental and theoretical trend graphs differ in shape due to experimental errors and the transient nature of varying experimental outdoor weather conditions. However, the experimental and theoretical result trends agree.

4. Conclusions

Mild steel plate and galvanized iron pipes can make thermal absorption components of a flat plate solar water heater. Aluminum sheet and copper pipes have been widely used for making commercial solar water heaters. The instantaneous heat gain by our research flat plate solar water heater shows that adequate thermal energy can be obtained for solar water heating. The heat gained by the solar collector is directly proportional to solar radiation intensity, aperture area, and absorption transmittance product.

Thermal storage fluids improve the output temperature from the solar collectors. However, the output temperature from the solar water heating system depends on the thermo-physical properties of the thermal storage fluids. For instance, sunflower oil produces a higher output temperature than water as thermal storage media from a flat plate solar water heater. From the research findings, it was also noted that thermal storage fluids increase the quantity of stored heat by the solar collector, hence increasing the temperature of the inlet fluids into the solar collector.

Thermal storage fluids improve the thermal performance of a solar collector by reducing thermal losses within the system. Sensible heat storage technology has advantages in terms of low cost and use of non-toxic materials. Sunflower oil has better heat retention ability than water and air. Thus, sunflower oil can conserve heat for a longer period.

It can also be concluded that the thermal storage medium improves the heat removal factor of a solar water heater. The heat removal factor, as a measure of the heat exchange process within the system, greatly depends on the thermal conductivity of the storage medium. For instance, the higher heat removal of sunflower oil than water is attributed to its greater thermal conductivity. Thermal storage fluids reduce the overall heat loss coefficient of a solar water heater. Sunflower oil has a lower heat loss coefficient than that of water and air. The heat loss coefficient of air is high due to its high convective heat loss coefficient. This explains why the solar collector output temperatures associated with thermal storage fluids are higher than the conventional ones.

The efficiency of a solar water heater can be enhanced by thermal storage fluids. The efficiency of sunflower oil is higher than that of water as a thermal storage fluid. This shows that sunflower oil produces higher usable thermal power output than water from equal incident radiation on the solar collector surface. Water can also be used as both HTF and TSF, but it has lower efficiency than sunflower oil. Sunflower oil has the highest collector efficiency factor, followed by water and air, implying that of the three media, sunflower oil has the highest rate of heat transfer from the absorber surface to itself as a heat transfer fluid. Heat removal factor FR, for the three fluids, also follows the same trend as that of the collector efficiency factor. From the heat removal factor values, which show the effectiveness of a fluid in the heat exchange mechanism, our research findings showed that sunflower oil is better than water and air as HTF. Thus, sunflower oil is also good as a thermal storage fluid since it has a low heat loss coefficient. However, despite its high cost, sunflower oil is a better thermal storage medium than water and also more suitable for higher temperature applications due to its high boiling point of 229℃ - 230℃ and flash point of 250℃.

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