ABSTRACT HEADING

The performance of solar-assisted water heaters is limited by the absorption properties of the working fluid and it can be improved by replacing them with highly conductive nanofluids. However, the idea of using nanofluids have not been completely commercialized and many works are only being focused on the steady-state analysis of Solar Assisted Water Heaters (SAWH) which don't reflect a practical scenario. Hence, this works aims at analyzing the performance of a SAWH installed in a multi-residential building in Greece Climatic Conditions using TRNSYS and MATLAB with aluminium oxide nanofluid as the working fluid. It was found that upon including 0.1% volume concentration and 13 nm particle-sized aluminium oxide nanofluid, the annual energy consumption dropped from 330 kWh to 279 kWh. Further, the maximum energy and exergy efficiency increased to around 52% and 2.5% respectively. Upon performing the exergy analysis, it was found that the contribution of exergy destruction between the plate and the fluid is only about 20% of the total exergy destruction. Though this percentage is small, this works aims at reducing this component of exergy destruction for further enhancement of the system. It can be finally concluded that adding nanofluids to the system is a prudent option of increasing the performance. However, around 80% of the total exergy destruction occurs in the flat plate collector. Hence, a novel change in the design of the collector is essential to reduce this part of exergy destruction and to improve the system's performance.

INTRODUCTION

Energy is primarily required in many fields like mining, travel, buildings, food, etc., Amongst various energy demands, buildings consume a major portion of energy. For example, about 38% of the total energy consumption in the European Union (EU) is for buildings (Panagiotidou, Aye, and Rismanchi 2020). Primarily, the energy is used to satisfy the thermal requirements of the building. For example, the Heating Ventilation and Air Conditioning (HVAC) systems are accountable for the major portion of building energy consumption: about 50% in the U.S. Further, the heating demand accounted for nearly 10-40% of the total energy consumption in the year 2000 in China (Baneshi and Bahreini 2018).

Under HVAC, water heating is a major domain where the thermal requirements need to be satisfied. For example, water heaters can be used for both hot water consumption and also for space heating. In many parts of the world, they are a major source of energy consumption. For example, in Iran, about 80% of the building energy is used for hot water production and space heating (Baneshi and Bahreini 2018).

The actual problem arises when these energy demands are met by conventional energy sources like electric heaters, natural gas and coal-based heaters. The enormous energy demands put in front of vanishing fossil fuels and expensive clean energy gives rise to energy poverty, where even in places like Europe between 50 and 125 million people are unable to afford proper indoor thermal comfort (Souliotis et al. 2018). Studies on energy poverty have shown that the current economic pressure directs people to exploit the possibility of non-renewable fuels like wood, carbon and biomass even though they are harmful to the environment. For example, in 2013, UK'S total energy consumption was about 205 million tons of oil and about 31% was consumed for domestic applications like water heating and space heating (Buker and Riffat 2016).

The only way in which this problem can be solved is by shifting to a system that is environmentally friendly SAWH. However, the performance of such systems is highly limited by the design of the collector and the thermal properties of the working fluid. This work aims at improving the performance of SAWHs by replacing the conventional working fluid with 0.1% volume concentration, 13 nm particle size aluminium oxide nanofluid

(Hawwash 2018).

Nanofluids are a suspension of metallic or non-metallic nanoparticles in a base fluid. Nanofluids experience a substantial increase in thermal conductivity, liquid viscosity and heat transfer coefficient when compared to base fluids (Yousefi 2012). They conducted an experimental investigation and found that aluminium oxide-based nanofluids showed 28.3% increase in thermal efficiency in the flat plate collectors. Goel et al., (Goel, Taylor, and Otanicar 2020) found five per cent increase in the efficiency by using a diversity of nanofluids. Hawwash et al., (Okonkwo et al. 2020) studied the effect of aluminium oxide nanofluids with six different volume fractions 0.1-3% on flat plate collectors. They found that the nanofluid improves the thermal efficiency until 0.5% volume concentration and the performance dips with any further increase in the concentration. Said et al.,(Said, Saidur, and Rahim 2016) numerically and experimentally investigated the energy and exergy efficiency of a flat plate solar collector using different sizes of aluminium oxide-based nanofluid. They found that aluminium oxide water 13 nm nanofluid with 0.1% volume concentration and at a flow rate of 1.5 kg/min showed the highest energy efficiency. Increasing the volume concentration may seem to be an attractive option owing to its enhanced thermal conductivity. But the resulting increased friction due to the increased viscosity tends to bring down the efficiency (Okonkwo et al. 2020).

In addition to improving the efficiency, nanofluids also have an advantage that they reduce the size requirements of collectors with their enhanced heat transfer and the design becomes more compact (Faizal et al. 2013).

To the best of author's knowledge, the transient exergy and energy analysis of nanofluids on SAWHs have not been considered so far for the considered case study and location. The present work provides a comprehensive investigation of annual energy consumption, energy and exergy efficiency, exergy destruction and the thermophysical properties of nanofluids in a flat plate collector by also considering the effect of actual irradiation data.

METHODOLOGY

This investigation is aimed at replacing conventional electric water heaters with the novel SAWHs suggested in this study for a typical multi-residential building in Thessaloniki, Greece. It was carried out by simulating the SAWHs that reflected a practical scenario in TRNSYS. The annual energy demand was calculated using the latter and the exergy analysis was carried out using MATLAB.

Case Study

Though it is well known that solar energy is abundant and resourceful, the actual potential of solar energy can be only realized when it is implemented. Greece stands a huge potential and is a probable option for installing SAWHs because according to Greek building code (Panagiotidou, Aye, and Rismanchi 2020), any building that undergoes a major renovation must have a solar thermal system capable of supplying 60% of SHW needs. Also, it is the second-largest country in the EU in terms of installed solar thermal systems.

The building under consideration is a 6-storeyed multi-family residential building with a basement floor and with 27 apartments (Panagiotidou, Aye, and Rismanchi 2020). The building that was constructed before 1980 was selected as more than 50% of the buildings constructed during that time have insufficient heating systems. Also, according to Greek regulations for building energy efficiency, on an average, a person consumes 50 liters of water per day (Okonkwo et al. 2020; Panagiotidou, Aye, and Rismanchi 2020). Assuming every apartment has around 3 people, the demand is considered to be 150 liters. The guidelines provided by the National Renewable Energy Laboratory (NREL) was used to calculate the Direct Hot Water (DHW) profile in this work as it is more appropriate (Hendron and Burch 2007).

Considering the rooftop geometry and orientation, the maximum panel area which can be installed in the roof is 81 m^2. Given there are 27 apartments, each one would have around 3 m^2 panel ara. Further, in this work, same water draw profile was considered as Panagiotidou et al., (Panagiotidou, Aye, and Rismanchi 2020).

Testing Method for Simulation

ASHRAE Standard 86-93 (ASHRAE Standard 1985) is one of the widely followed methods to evaluate the thermal performance of flat plate and concentrating solar collectors. Eric et al., (Okonkwo et al. 2020) followed the procedure and found the values of thermal efficiencies for a combination of incident radiation, ambient temperaure and inlet fluid temperature having 0.1% volume concentration aluminum oxide nanofluid as the working fluid. Using the technique of curve fitting, this curve can be used to evaluate the coeficients of the efficiency equation which inturn can be used in TRNSYS for simulation (University of Wisconsin--Madison. Solar Energy Laboratory 1975).

SYSTEM DESCRIPTION

Electric Water Heater

A typical electric water heater used in residential buildings was modelled in this work (Panagiotidou, Aye, and Rismanchi 2020). The water coming from the mains was preheated by the hot water in the storage, which then entered the heating coil for further heating. The setpoint temperature was 60 ^oC. Using TRNSYS, Type 6 was taken as the heating coil of 3600 W capacity and type 4c was taken for modelling the storage tank of 200 l capacity (Panagiotidou, Aye, and Rismanchi 2020). The tank was simply used to store the hot water with minimal thermal losses and didn't have heating coils in it.

Solar Thermal Water Heater

A typical SAWH shown in Figure 1 consists of 2 loops: primary and secondary. In conventional water heaters, water would be the circulating in the primary loop; in this work, the aluminum oxide was taken as the novel working fluid. The nanofluid upon entering solar collector got heated up after absorbing the irradiation and gave up the heat to the incoming freshwater from mains through the heat exchanger.

The controller signaled the pump to circulate fluid only when the temperature of the incoming water from the storage tank was greater than the temperature of the fluid in the primary loop by atleast 10 ^0C. The hot water was then stored in the storage tank for practical use. In TRNSYS, the solar collector, heat exchanger, controller and storage tank was modelled using type 1b, type 5b, type 2b and type 4c of TRNSYS respectively.

The specifications of the flat plate collectors are given in Table 1. The collector was assumed to be south facing with a slope of 45. The 200-l tank was divided into six temperature nodes to account for the stratification. To increase the effectiveness, instead of using a single heating coil in the tank, two heating coils; 2500 W and 1000 W coils were used in this work at the topmost node.

Table 1. Specifications of the selected flat-plate collector

Parameter	Value (Water)	Value (Aluminum Oxide Nanofluid)
Intercept Efficiency	0.56	0.5779
Efficiency Slope	1.88 kJ h^{-1} m^{-2} K^{-1}	2.07 kJ h^{-1} m^{-2} K^{-1}
Efficiency Curvature	2.27 kJ h^{-1} m^{-2} K^{-2}	1.421 kJ h^{-1} m^{-2} K^{-2}
1st Order IAM	0.2	0.2
2nd Order IAM	0	0
Collector Area	3 m^2	3 m^2
Flow Rate	200 kg/hr	200 kg/hr

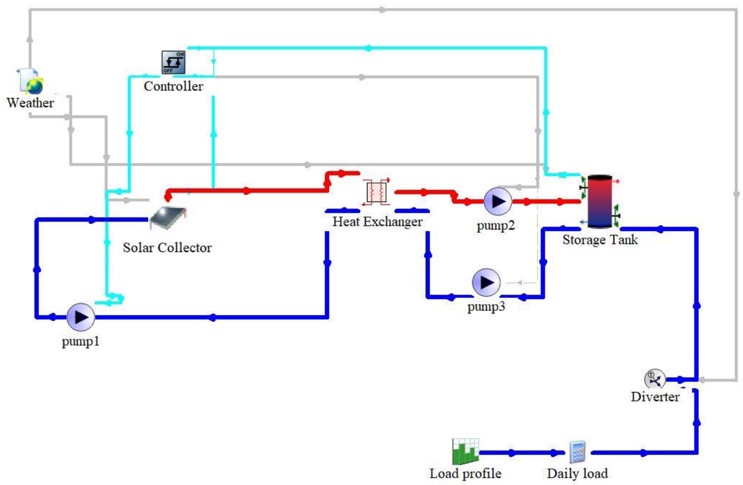

Figure 1 Model describing Solar Assisted Water Heater

THERMODYNAMIC ANALYSIS

This section presents the analysis obtained from the first and second law of thermodynamics. The useful energy gain of the flat plate collector can be given by the following equations (Kalogirou 2013):

$$Q_u = F_R A_C[(\tau\alpha)_n K_\theta G_t - C_1(T_i - T_o) - C_2(T_i - T_o)^2] \quad (1)$$

Efficiency can be written as:

$$\eta = \frac{Q_u}{G_t A_C} = F_R(\tau\alpha)_n K_\theta - \frac{F_R C_1(T_i - T_o)}{G_t} - \frac{F_R C_2(T_i - T_o)^2}{G_t} \quad (2)$$

Exergy analysis can be performed using the first and the second law of thermodynamics and can be defined as the maximum amount of work that can be derived from a system as it undergoes a change from its initial state to a final state that is in equilibrium with the surroundings. Exergy efficiency in comparison to energy efficiency gives us a better insight into the amount of maximum work that can be extracted from the system and into the possibility of any improvement. In other words, exergy analysis serves as a useful tool because it not only assesses the performance of the system but also gives a measure on the maximum capacity of the system.

The transient state was considered in this model and the exergy analysis was performed on the summer solstice.

It was assumed that the thermophysical properties of nanofluids were constant and the work transfer from the system and the heat transfer to the system were positive. Loss coefficient was assumed to be a linear function of temperature (Kalogirou 2013) and the exergy due to leakage was considered only for the entrance effect.

Largely steady sate analysis has been considered in the previous works. The dependence of exergy on mass flowrate nanoparticle concentration, particle size has been previously studied. However, research has not been done on the dependence of exergy on incident irradiation and their performance over a range of time. Such analysis would give us a better insight into the actual exergy destruction occurring over a day and can pave a path for potential improvements. The change in exergy while calculating the exergy destruction was considered in this work which was largely neglected in the previous works owing to their steady approach. The final and the initial points at each time step of the collector was taken to be the temperature of the fluid at that particular temperature. The exergy balance equations can be written as:

$$Exergy\ Rate_{In} - Exergy\ Rate_{Out} - Exergy\ Rate_{Destroyed} = \frac{d(Exergy)}{dt} \tag{3}$$

where, $$\frac{d(Exergy)}{dt} = Ex_2 - Ex_1 = \dot{m}[(u_2 - u_1) - T_o(s_2 - s_1)] \tag{4}$$

$$Exergy\ Rate_{Destroyed\ Sun\ to\ Plate} = G_t\, A_C\, (1 - \eta_o + \eta_o \frac{T_o}{T_P} - \frac{T_o}{T_S}) - \dot{m}\, C_P\, [\,(T_2 - T_1) - T_o \ln\frac{T_2}{T_1}] \tag{5}$$

$$Exergy_{\ Dest\ Plate\ -Fluid} = \dot{m}\, C_P\, T_o[2\ln\frac{T_2}{T_1} - \frac{(T_2 - T_1)}{T_P} - \frac{(T_2 - T_1)}{T_o}] \tag{6}$$

$$Total\ Exergy_{\ Destruction} = Exergy\ Rate_{Destroyed\ Sun\ to\ Plate} + Exergy_{\ Dest\ Plate\ -Fluid} \tag{7}$$

The exergy efficiency can be defined as the ratio of the increase in fluid flow exergy to the exergy of incident irradiation.

$$Exergy_{\ Efficiency} = \frac{\dot{m}\, C_P\ [\,(T_2 - T_1) - T_o \ln\frac{T_2}{T_1}]}{G_t\, A_C\, (1 - \frac{T_o}{T_S})} \tag{8}$$

In this work, the transient simulation was performed using TRNSYS, and with the help of thermodynamic states obtained from the software, using the above set of equations, the exergy analysis was performed on MATLAB.

THERMOPHYSICAL PROPERTIES OF NANOFLUID

The properties of nanofluids like thermal conductivity, specific heat capacity, viscosity and density should be determined by equations given below.Density and specific heat capacity are calculated by the following equations (Khanafer and Vafai 2011). These equations are widely used and have good agreement with experiments (Mahian et al. 2014).

$$\rho_{nf} = \rho_{nf}(1 - \phi) + \rho_p\, \phi \tag{9}$$

$$C_{p,nf} = \frac{\rho_f\, C_{p,f}(1 - \phi) + \rho_p C_{p,p} \phi}{\rho_{nf}} \tag{10}$$

Thermal conductivity and viscosity are taken from the empirical expressions found by Faroogh Garoosi et al., (Garoosi 2020) . These equations take into account the particle concentration, size and temperature dependence and have very good agreement with experiments (Mahian et al. 2014).

Using these set of equations and at 0.1% volume concentration, for 13 nm-sized aluminium oxide, the various thermophysical properties are presented in table 2.

Table 2. Thermophysical properties of nanofluid

$C_{p,nf}$	ρ_{nf}	μ_{nf}	k_{nf}
kJ/kg K	Kg/m^3	Pa s	W/m K
4.1654	999.97	6.99×10^{-4}	0.6317

RESULTS AND DISCUSSIONS

Net Electricity Consumption

This work compared the net annual electricity consumption of 3 systems namely: electric water heater, SAWH with water as the working fluid, and SAWH with water- aluminum oxide nanofluid as the working fluid. It was carried out for a multi-residential building in Thessaloniki, Greece (Panagiotidou, Aye, and Rismanchi 2020). As expected, the electric water heater had the highest electricity consumption of about 2000 kWh. Upon installing SAWH the electricity consumption reduced to 330 kWh and further dipped to the lowest point of 279 kWh upon adding the nanofluid.

The flat plate solar thermal collector could provide up to 83% of the total annual energy demand and it increased to about 86% upon adding nanofluid. These findings are in line with Maria et al., (Panagiotidou, Aye, and Rismanchi 2020), Matuska and Sourek (Matuska and Sourek 2015).

It has to be noted that given the small volume concentration if nanoparticle: about 0.1%; the amount of enhancement obtained is significant.

Energy Analysis

This section presents the results obtained from the first law of thermodynamics on a summer solstice day in the considered location. Figure 2 shows the temperature of fluid coming out from the solar collector and the storage tank to the load. As it can be seen, a significant portion of the thermal requirement was satisfied by the solar collector during noon. The temperature coming out of the storage tank to the load was maintained around 60 ^{o}C to satisfy the thermal requirements.

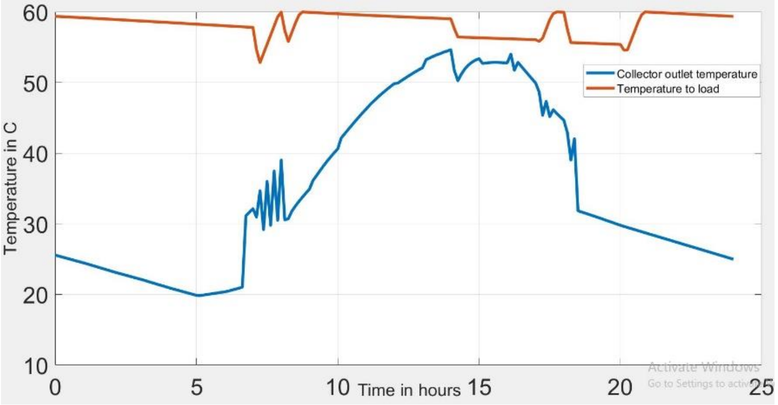

Figure 2 Variation of outlet temperature with time

Figure 3 shows the comparison of the efficiency of the flat plate solar collector with water and aluminium oxide nanofluid as the working fluid. The efficiency of the collector increased with the addition of nanofluid. Fluctuations could be seen during early morning and late evening hours because of the controller, which operates the pump circulating nanofluid only when the temperature in the solar collector exceeded by at least 10 ^{o}C. The lower value of efficiency improvement could be attributed to the fact that the solar collector was unable to convert the incident irradiation to useful energy gain. Any work aimed at improving the design of a solar collector can solve this problem. For example, works targeting on concentrating solar power or installing solar trackers can prove to be an effective solution as it would increase the performance of the collector by increasing their ability to absorb more irradiation.

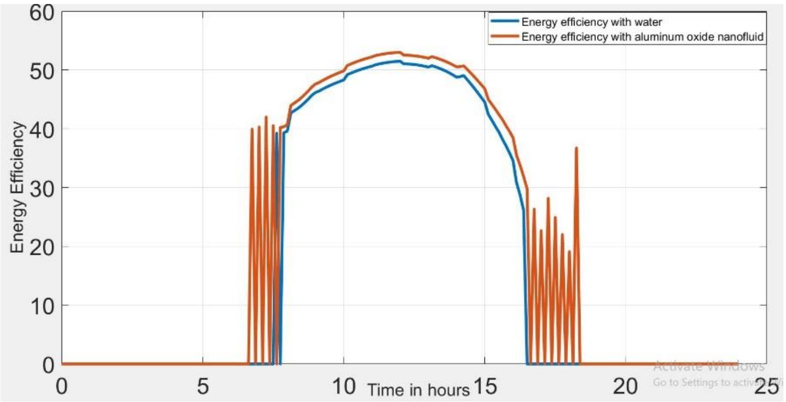

Figure 3 Variation of energy efficiency with time

Exergy Analysis

This section presents the results of analysis obtained from the second law of thermodynamics on a summer solstice day in Thessaloniki, Greece. Remarkably, about 21% increase in the exergy efficiency was found upon adding nanofluid: it increased from about 1.9 to 2.3%. Interestingly, higher improvement was found in exergy efficiency when compared to energy efficiency, which was mainly because of the reduction in exergy destruction between the plate and the fluid owing to enhanced heat transfer. Further, the Figure 4 shows various exergy destruction occurring in a flat plate collector in one full day. Also, it can be concluded that about 80% of the total exergy destruction occurred between the Sun and the plate and 20% of the total destruction occurred between the plate and fluid. It is because the collector has failed to capture the irradiation because of its simple structure, which could have otherwise been converted to useful energy gain. Hence, in addition to improving the heat transfer, it is a prudent option to improve the design of the collector, say by adding concentrators such that it reduces the exergy destruction between the plate and the Sun.

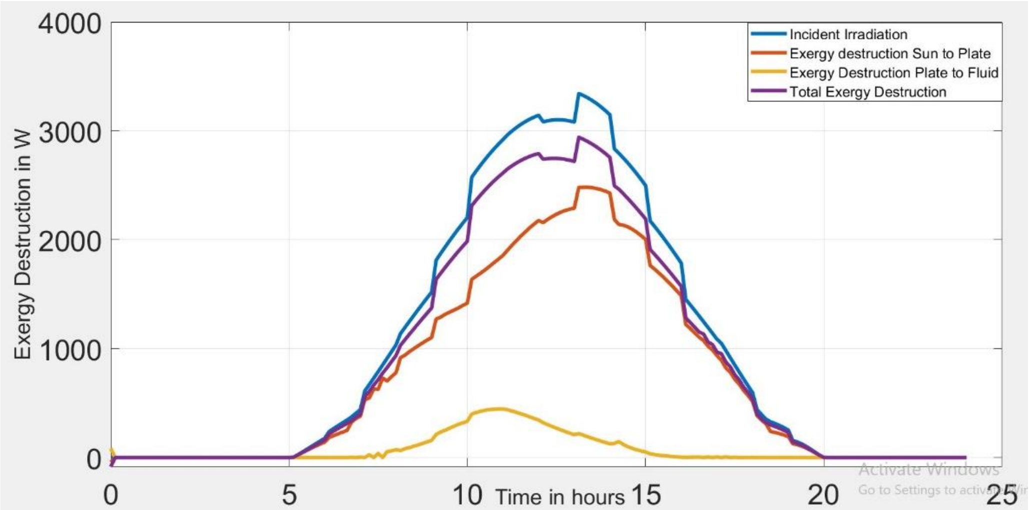

Figure 4 Variation of exergy destructions versus time

CONCLUSION

The effect of using aluminium oxide nanofluid as an absorbing medium in a flat plate solar water heater was investigated by simulating a practical water heater model in TRNSYS for a multi-residential building installed in Thessaloniki, Greece. As most of the previous works were targeted on steady-state analysis, this work focused on the transient effect of irradiation on annual electricity consumption, energy and exergy analysis. About 86% of the total electricity consumption was satisfied by adding 0.1% volume concentration of 13 nm-sized aluminium oxide nanoparticles. The exergy efficiency increased to more than 2% achieving about 21% rise upon adding the nanofluid. It was also found that about 80% of exergy destruction occurred between the sun and the plate specifically during daytime which was mainly because of the structural flaw in flat plate collector. This can be rectified by using concentrated solar power technology thereby focusing more irradiation on the collector and reducing the exergy destruction between the plate and the sun.

NOMENCLATURE

Q_u = Useful Energy Gain in W

F_R = Heat Removal Factor

A_C =Aperture Area of Collector in m^2

$(\tau\alpha)_n$ = Transmittance Absorbtance product of normal irradiation

K_0 = Incidence Angle Modifier

G_t = Incident Irradiation in W/m^2

T = Temperature

T_s = Apparent Sun Temperature; 3/4th of black body temperature of the sun. It is assumed to be 4500 K in this work (Jafarkazemi and Ahmadifard 2013)

$\dot{m}$ = Mass Flow Rate in kg/s

u = Internal Energy in J/kg

s = Entropy in J/kg K

Ex = Exergy in W

η_o = Optical Efficiency; Taken as 0.84 (Faizal et al.2013)

C_P = Specific Heat Capacity of Fluid in J/kg K

Subscripts

i = Inlet

o = Ambient

1 = Initial State Point

2 = Final State Point

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