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Numerical Analysis of Solar Water Heater using Water-Glycerin Solution

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Abstract

A popular use of solar energy is heating water in domestic systems. Solar heating has been found to be viable in many parts of the world and is also simple. Solar water heating is the conversion of sunlight into renewable energy for water heating using a solar thermal collector. Fluid, usually water, in contact with the absorber collects the trapped heat to transfer it. The most basic approach to solar heating of water is to simply put a tank filled with water into the sun. The heat from the sun would heat the metal tank and the water inside. This was how the very first SWH systems worked more than a century ago. However, this setup would be inefficient because there is little to limit the heat loss from the tank. Adding an insulated box around the tank, and adding glass above the top where the sun comes in would do a lot to retain heat. In this work, a numerical investigation was carried out where glycerin and water solution were used for heating. Using the ANSYS simulation software, we have modelled our system and compared the data with only water-based heaters.
Keywords: ANSYS, SWH, Solar energy

1. Introduction

A solar water heater (SWH) consists of a solar collector array, an energy transfer system, and a storage tank. The solar collector array collects the sunlight, absorbs the radiation and converts it into thermal energy [1]. This heat is then absorbed by a heat transfer fluid (water, non-freezing liquid, or air) that passes through the collector. This heat can then be stored or used directly. The collector itself could be either a black-painted flat-plate absorber bonded to copper piping and covered with a transparent glass (flat-plate collector) or copper tubing surrounded by evacuated and selectively coated glass tubes (evacuated-tube collector) [2]. A large part of the energy is absorbed by the collector and transferred to the fluid, usually a mixture of water and anti-freeze. This mixture is then pumped by an active system or transported naturally via convection through the collector to a coil heat exchanger at the bottom of a cylinder tank (indirect system), where the heat is further transferred to a storage tank or is used directly [3]. There are two classifications of SWH systems, passive and active systems [4]. Passive systems are most widely used in domestic systems and involve heat transfer from collector to tank via natural circulation, at a temperature of 60^{o}C [5]. In contrast, active systems use an electric pump to circulate water through the collector. A check valve may be required to prevent reverse water circulation [4]. An active SWH has an efficiency that is between 35%-80% [6]. A passive system has an efficiency in the range of 30%-50% [5]. Despite the resourcefulness of SWH, there are economic barriers that are preventing the large scale utilization of SWH's in developing nations [2]. These barriers include (but are not limited to): low level of income, shortage of energy policies, lack of long term investments and lack of public awareness [7]. In developing nations, the principal barriers are poor promotion of SWH and a poor understanding by the general public [8]. In our investigation, we took 4 water glycerin based binary solutions of different concentrations. The study was carried out in ANSYS FLUENT and the found results were compared with only water-based heaters. It was found that adding glycerin with water increases its heat absorbent and higher temperatures can be achieved for same solar irradiation from this system.

2. Materials and method

For this analysis, the system was first designed using CAD software. The length of the total pipe was 9.144 m and 11 turns were made to make the coil. The pipe used for the flow was made of copper. The flow of the water was due to gravitational acceleration, no external pump was used. To get the maximum solar exposure, the whole system was aligned with the Geographical latitude. Figure 1 shows the pipe system.

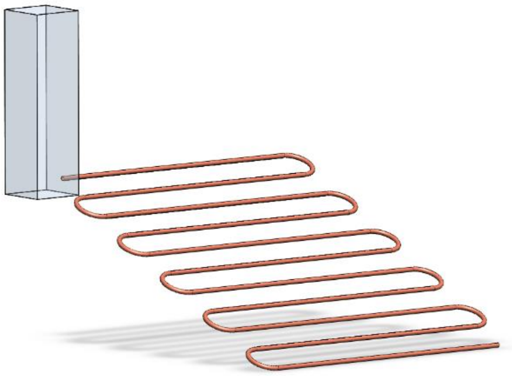

Figure 1. Gravity feed water heater

The used fluid was both water and water-glycerin binary solution. For the binary solution four different concentrations were taken. The concentrations and their properties are given in Table 1.

Table 1

Solution	Density (kg/m^3)	Specific Heat (kJ/kg.K)	Thermal Conductivity (W/m.K)	Dynamic Viscosity (cP)
Water/Glycerin-20%	1051.5	3.826	0.4958	3.282
Water/Glycerin-30%	1077.9	3.610	0.4665	4.647
Water/Glycerin-40%	1106.8	3.358	0.4339	7.532
Water/Glycerin-50%	1135.6	3.127	0.4039	13.32

3. Model development

For the numerical analysis, the following assumptions were made.

1. The fluid is homogeneous.
2. The wall thickness of the pipes is same throughout the length.
3. The inlet velocity of the fluids does not change with time.
4. There is no internal heat generation due to friction or viscous effect.
5. The system is free from all sorts of contamination so that the fouling factor does not need to be considered.

For numerical analysis, shear-stress transport $k-\omega$ model was used for turbulence modeling. The model consists of the following equations.

Shear stress Transport $k-\omega$ model works on the following governing equations where k represents the turbulence kinetic energy and ω gives the specific dissipation rate.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\Gamma_k\frac{\partial k}{\partial x_j}\right]+G_k-Y_k \quad \ldots (1)$$

$$\frac{\partial}{\partial t}(\rho \omega)+\frac{\partial}{\partial x_j}(\rho \omega u_j)=\frac{\partial}{\partial x_j}\left[\Gamma_\omega\frac{\partial \omega}{\partial x_j}\right]+G_\omega-Y_\omega+D_\omega \quad \ldots (2)$$

In these equations, the term G_k represents the production of turbulence kinetic energy. G_ω represents the generation of ω. Γ_k and Γ_ω represent the effective diffusivity of k and ω respectively. Y_k and Y_ω represent the dissipation of k and ω due to turbulence. D_ω represents the cross-diffusion term. The SST $k-\omega$ model is based on both the standard $k-\omega$ model and the standard $k-\varepsilon$ model. To blend these two models together, the standard $k-\omega$ model has been transformed into equations based on k and ω , which leads to the introduction of a cross-diffusion termD_ω, defined as

$$D_\omega = 2(1-F_1)\rho \frac{1}{\sigma_{\omega,2}} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (3)$$

ρ is defined as the density of the fluid. u_i and u_j are the velocity components composed of mean and fluctuating velocity components ($i = 1,2,3, \dots$).
The effective diffusivities for the $k-\omega$ model are given by

$$\Gamma_k = \mu + \frac{\mu_t}{\sigma_k} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4)$$

$$\Gamma_\omega = \mu + \frac{\mu_t}{\sigma_\omega} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (5)$$

Where σ_k and σ_ω are the turbulent Prandtl numbers for k and ω respectively. The turbulent viscosity, μ_t , is computed by combining k and ω as follows:

$$\mu_t = \frac{\rho k}{\omega} \frac{1}{max\left[\frac{1}{\alpha^*}, \frac{SF_2}{\alpha_1 \omega}\right]} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

Production of k
The term G_k represents the production of turbulence kinetic energy. From the exact equation for the transport of, this term may be defined as

$$G_k = -\rho \overline{u_i' u_j'} \frac{\partial u_j}{\partial x_i} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (7)$$

Where, u' term represents the fluctuating velocity components.
Production of ω
The term G_ω represents the production of ω and is given by

$$G_\omega = \frac{\alpha}{v_t} G_k \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (8)$$

Dissipation of k
The dissipation of k is given by

$$Y_k = \rho \beta^* f_{\beta^*} k \omega \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (9)$$

Dissipation of ω
The dissipation of ω is given by

$$Y_\omega = \rho \beta \omega^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (10)$$

The concept of conservation of energy is used to determine the heat transfer for the system. The governing equation is as follows.

$$\frac{\partial}{\partial t}(\rho E) + \nabla.(\vec{v}(\rho E + p)) = \nabla.\left(k_{eff} \nabla T - \sum_j h_j \vec{J_j} + (\overline{\overline{\tau_{eff}}}.\vec{v})\right) \dots\dots\dots\dots (11)$$

Here k_{eff} is the effective conductivity$(k + k_t)$. Where k_t is the turbulent thermal conductivity, defined according to the turbulence model being used, and $\vec{J_j}$ is the diffusion flux of species j. The first three terms on the right-hand side of Equation represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. For radiation modeling Discrete Ordinates (DO) model was used.

4. Boundary conditions

The boundary condition for this analysis was both thermal and hydrodynamic. The mass flow rate of the inlet was defined to be 0.00142 kg/s. The thermal boundary condition basically consists of radiation. By using solar ray tracing, the fair-weather condition was modelled and used for the analysis. Moreover, insulation condition was applied so that no heat loss should take place.

5. Results and discussion

In this section, the performance of four glycerin-water solution has been compared with normal water heater. The performance has been calculated in terms of outlet temperature and efficiency of the system. The results show that the solution Water/Glycerin-50% gives the maximum efficiency for a particular system.

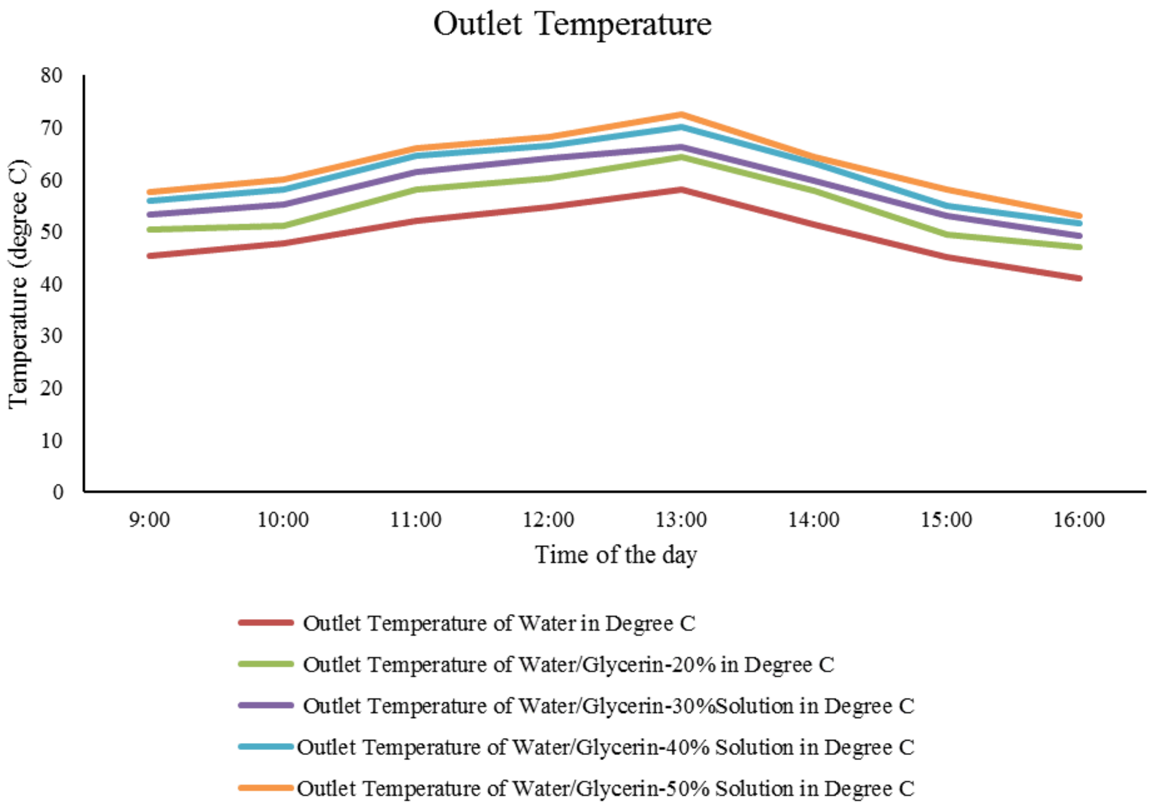

Figure 2. Outlet temperature of the system for different fluid

Figure 2 shows the outlet temperature for different solutions. The graph shows that the maximum temperature is achieved at the 13th hour of the day for all the solutions. However, the maximum outlet temperature is achieved by the Water/Glycerin-50% solution. The second solution that has been reached most close to the previous one is Water/Glycerin-40%. The curve for Water/Glycerin-30% solution remains in 3rd position. It can be seen that the increase in glycerin in solution increases the performance of the system.

Efficiency: FIGURE 3 shows the efficiency of the system for all the solutions. The performance however increases with the increase in percent of glycerin in the solution. The Water/Glycerin-50% solution gives the maximum efficiency and the only water gives the lowest efficiency. The equation used for calculating the efficiency is as follows.

$$\eta = \frac{\dot{m} C_p \Delta T}{IA} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (12)$$

Where, $\dot{m}$ is the mass flow rate in kg, C_p is the heat capacity at constant pressure, ΔT is the temperature difference between inlet and outlet, I is the solar intensity and A is the effective surface area.

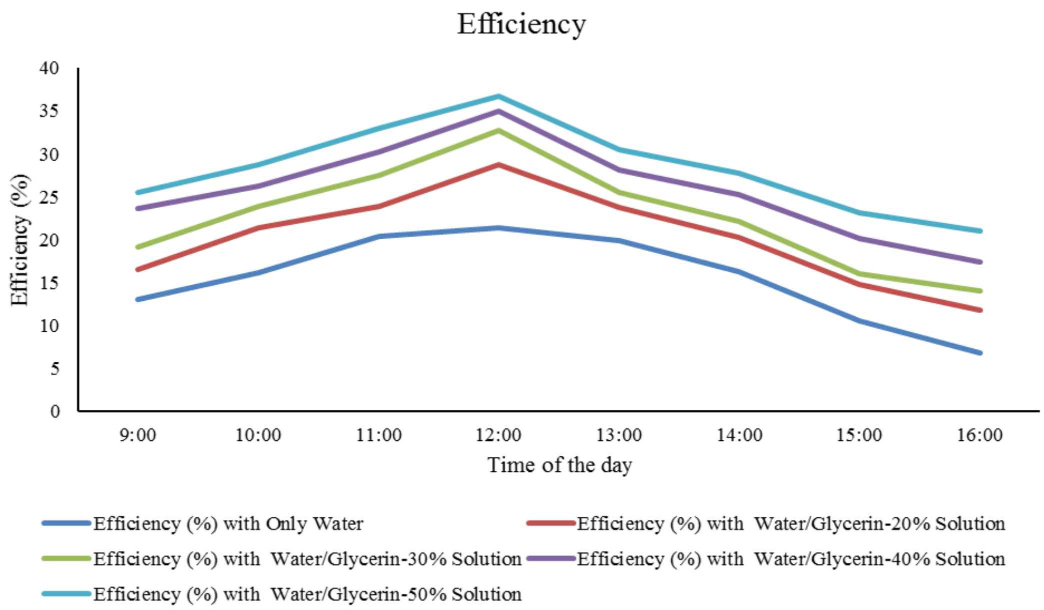

Figure 4. Efficiency of the system for different fluid

The reason behind the increase in efficiency for Water/Glycerin solution is the change in solution property which enables the system to give higher outlet temperature and higher efficiency. It helps the water to absorb more solar heat energy which in turn increases its efficiency.

6. Conclusion

The performance of water heater analyzed in this study will have a great impact on selecting the required solution for a particular system. The use of water solution is an old technique yet a tested one. The addition of foreign material increases the heat absorption capacity of water which increases the performance of the system. The found results in this study also support this theory. The Water/Glycerin-50% solution has the maximum efficiency and outlet temperature and can be recommended for any solar water collector.

7. References

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