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Analysis of experimental results on a conical solar water heater

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Abstract. Today, globally the consumption of energy from organic fuels is decreasing, and the rational use of thermal energy from solar radiation is one of the current tasks. In particular, in buildings and facilities, in the energy sector and other industries, efficient use of thermal energy is important. The scarcity of organic energy sources, high energy costs, and the negative environmental impact of energy production are significant factors. Renewable energy tech-nologies are rapidly developing worldwide, achieving high technical-economic performance, and the production of thermal and electric energy based on hydrocarbon fuels and nuclear energy is beginning to compete with traditional technologies. The most intensive development is observed in countries with high energy import demand and high energy tariffs. At the same time, renewable energy in the near future will occupy an important place in the energy sector of all countries, including those rich in organic fuels. Therefore, supporting research and development in advanced renewable energy technologies is of particular importance. For increasing national scientific-technical capacity and preventing complete technological dependence on imported technologies and equipment, this remains an important task for many countries.

INTRODUCTION

Electricity and thermal energy are an integral part of every industry worldwide, and the growing demand for them makes the task of providing consumers with uninterrupted and high-quality electricity and heat supply particularly important [1]. New-generation technologies conduct scientific research on the implementation of advanced technologies and equipment that allow for the efficient and economical use of energy, fuel, and energy resources in heat supply systems [2]. As is known, natural fuels and energy resources used on an industrial scale today are gradually depleting; therefore, the use of renewable energy sources helps to preserve natural resources and maintain the environmental situation at the existing level [3]. This article analyzes the results of experimental studies of a solar water heater with a conventional tank, as well as with a conventional tank, a reflector, and a tubular solar water heater, and evaluates its energy efficiency and reliability. The distribution of heat in the working chamber of a conical solar water heater collector is a very complex physical process. This is due to the fact that several differential equations must be taken into account in this case. The heat conduction equation in solids and liquids, as well as the Navier–Stokes equations describing the motion of liquids or gases, are solved simultaneously [4-6].

Analysis of the experiment and the obtained results. The heat conduction equation in solids is written as follows:

$$\rho C_p \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + Q + Q_{ted}; \quad (1)$$

You are correct—the equation presented describes heat conduction in solids. Here, I would like to clarify the notation to avoid confusion:

ρ — material density (kg/m³);
c — specific heat capacity of the material at constant pressure (J/(kg·K));
k — thermal conductivity coefficient of the material (W/(m·K));

Q — power of internal heat sources (W/m³), sometimes denoted.

$$
\begin{aligned}
&J_i = \varepsilon_i e_b(T) FEP_i(T) + \rho_{d,j} G_i \\
&G_i = G_{m,i} + G_{amb,j} + G_{ext,j} \\
&G_{amb,i} = F_{amb,j} \varepsilon_{amb} e_b(T_{amb}) FEP_i(T_{amb}) \\
&e_b(T) = n^2 \sigma T^4,\ FEP_i(T) = \frac{15}{\pi^4} \int_{C_2/(\lambda_i - l^T)}^{C_2/(\lambda_i T)} \frac{x^3}{1-e^x} dx
\end{aligned} \tag{2}
$$

You have listed important parameters related to radiative heat transfer that must be taken into account when modeling a conical solar water heater [7-8]. Let us examine them in more detail and relate them to the Navier–Stokes equation, which describes the motion of the fluid (water) inside the heater.

$$
\begin{cases}
\dfrac{\partial \rho}{\partial \tau} + \dfrac{\partial \rho V_x}{\partial x} + \dfrac{\partial \rho V_y}{\partial y} + \dfrac{\partial \rho V_z}{\partial z} = 0. \\
\rho \dfrac{\partial V_x}{\partial \tau} + \rho V_x \dfrac{\partial V_x}{\partial x} + \rho V_y \dfrac{\partial V_x}{\partial y} + \rho V_z \dfrac{\partial V_x}{\partial z} + \dfrac{\partial p}{\partial x} = \\
= \dfrac{\partial}{\partial x}\left(\nu\rho \dfrac{\partial V_x}{\partial x} \right) + \dfrac{\partial}{\partial y}\left(\nu\rho \dfrac{\partial V_y}{\partial y} \right) + \dfrac{\partial}{\partial z}\left(\nu\rho \dfrac{\partial V_z}{\partial z} \right); \\
\rho \dfrac{\partial V_y}{\partial \tau} + \rho V_x \dfrac{\partial V_y}{\partial x} + \rho V_y \dfrac{\partial V_y}{\partial y} + \rho V_z \dfrac{\partial V_y}{\partial z} + \dfrac{\partial p}{\partial y} = \\
= \dfrac{\partial}{\partial x}\left(\nu\rho \dfrac{\partial V_y}{\partial x} \right) + \dfrac{\partial}{\partial y}\left(\nu\rho \dfrac{\partial V_y}{\partial y} \right) + \dfrac{\partial}{\partial z}\left(\nu\rho \dfrac{\partial V_y}{\partial z} \right); \\
\rho \dfrac{\partial V_z}{\partial \tau} + \rho V_x \dfrac{\partial V_z}{\partial x} + \rho V_y \dfrac{\partial V_z}{\partial y} + \rho V_z \dfrac{\partial V_z}{\partial z} + \dfrac{\partial p}{\partial z} = \\
= \dfrac{\partial}{\partial x}\left(\nu\rho \dfrac{\partial V_z}{\partial x} \right) + \dfrac{\partial}{\partial y}\left(\nu\rho \dfrac{\partial V_z}{\partial y} \right) + \dfrac{\partial}{\partial z}\left(\nu\rho \dfrac{\partial V_z}{\partial z} \right) - F_z;
\end{cases} \tag{3}
$$

You have presented the components of the Navier–Stokes equation, which describes the motion of a viscous incompressible fluid. Let us clarify the notation and then proceed to the heat conduction equation in a liquid.

You are absolutely correct. The heat conduction equation in a liquid differs from the heat conduction equation in a solid by the presence of a convective term, which accounts for heat transport by the moving fluid.

$$
\begin{cases}
\rho C_p \dfrac{\partial T_2}{\partial \tau} + \rho C_p V_x \dfrac{\partial T_2}{\partial x} + \rho C_p V_y \dfrac{\partial T_2}{\partial y} + \rho C_p V_z \dfrac{\partial T_2}{\partial z} = \\
= \dfrac{\partial}{\partial x}\left(k \dfrac{\partial T_2}{\partial x} \right) + \dfrac{\partial}{\partial y}\left(k \dfrac{\partial T_2}{\partial y} \right) + \dfrac{\partial}{\partial z}\left(k \dfrac{\partial T_2}{\partial z} \right) + Q + Q_p + Q_{vd};
\end{cases} \tag{4}
$$

The fourth equation is analogous to the first one; however, the main difference lies in the addition of a convective term, which takes into account the velocity of the fluid flow [9-11].

The heat transfer coefficient in convective heat exchange:

$$
h = \frac{k}{D_h} Nu \tag{5}
$$

k — thermal conductivity coefficient of the heat-transfer fluid;

Nu — Nusselt number;

Hydraulic (equivalent) diameter, which is defined as follows:

$$D_h = \frac{4Wd}{2(W+d)} \tag{6}$$

d — equivalent (hydraulic) diameter of the channel (m). $\mathrm{Re} < 340$

$$Nu = 5.4 + \frac{0.00190\left[\mathrm{Re}\,\mathrm{Pr}\left(\frac{D_h}{L}\right)\right]^{1.71}}{1+0.0053\left[\mathrm{Re}\,\mathrm{Pr}\left(\frac{D_h}{L}\right)\right]^{1.71}} \tag{7}$$

where Re — Reynolds number; Pr — Prandtl number; L — channel length. $340 \le \mathrm{Re} \le 3400$

$$Nu = 0.116\left(\mathrm{Re}^{2/3} - 125\right)\mathrm{Pr}^{1/3}\left[1+\left(\frac{D_h}{L}\right)^{2/3}\right]\left(\frac{\mu}{\mu_w}\right) \tag{8}$$

where μ(T) — dynamic viscosity of the heat-transfer fluid at temperature T;
$\mu(T_0)$ — dynamic viscosity of the heat-transfer fluid at temperature T_0 [12-14].

The proposed technology—a simple tank-type, reflector-based, and tubular solar water heater—has been developed by improving existing systems and allows for a significant increase in energy efficiency [8].

This system offers the following advantages. Reflectors. Optimized for efficient collection of solar energy and its direction into the working chamber [15-18]. This ensures maximum utilization of solar radiation. Tubular system. Provides variable and turbulent water flow, which promotes heat transfer throughout the volume. Additionally, by activating the heat transfer surface and water movement, the effective heat transfer area increases, thereby improving thermal efficiency [19-22]. Thanks to the improved design, the heat transfer power and efficiency indicators have increased by 15–20%. This has a significant positive effect on the speed and stability of water heating in the solar water heater.

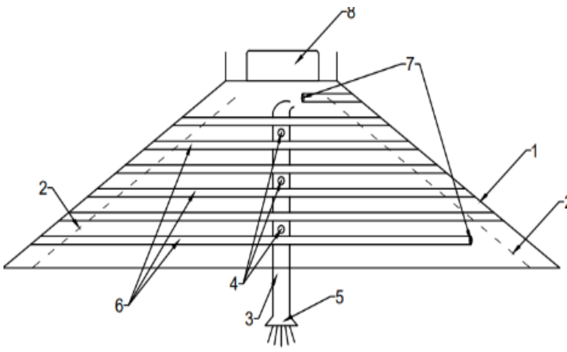

FIGURE 1. 1 – darkened metal surface (absorber), 2 – deflector, 3 – water outlet channel, 4 – auxiliary rubber hose for hot water outlet, 5 – valve, 6 – water channels, 7 – auxiliary channel, 8 – cover.

The device helps enhance energy efficiency and raise water temperature in a short time, which is especially important in regions with low solar radiation intensity. The distribution of heat in the working chamber of a conical solar water heater collector is a very complex physical process. This is because several differential equations are combined in the calculations. The heat conduction equations in solids and liquids, as well as the Navier–Stokes equations describing fluid or gas motion, are solved simultaneously [23-26]. The height of the solar water heater's shower chamber is 200 cm, and the height of the absorber is 27.5 cm. The large diameter of the cone is 100 cm. The water supply pipe (4) is positioned up to the inner part of the absorber. Holes for water outlet are opened every 40 mm. The water supply pipe of the solar water heater is installed opposite the water outlet pipe. To supply water into the copper pipe within the absorber (1, 2), inlet pipes are inserted, with a diameter of 12 mm for these copper water supply pipes [27-29]. The body (7) of the solar water heater is made of galvanized sheet with good thermal conductivity, which ensures minimal heat losses in the working chamber of the device.

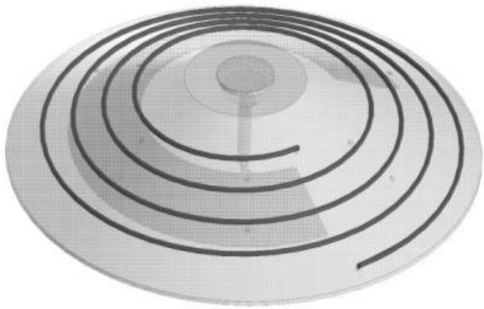

FIGURE 2. Discretization of a simple tank solar water heater with reflector and tubular system

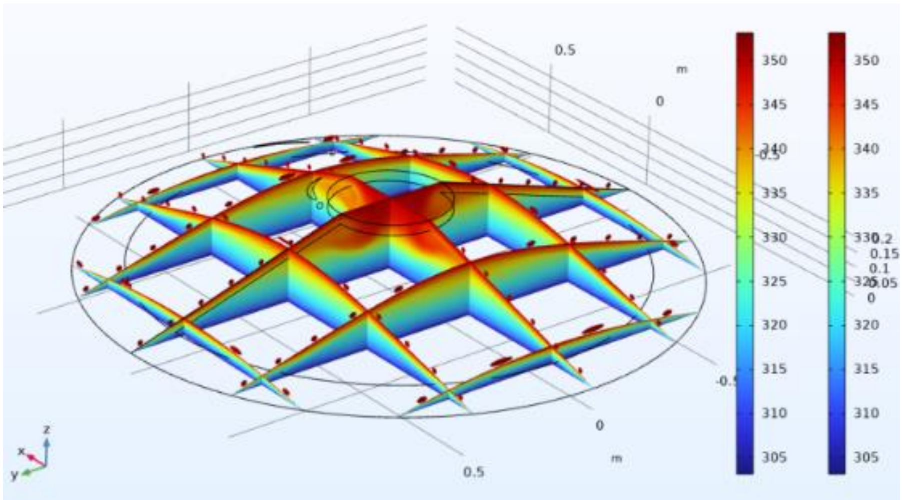

FIGURE 3. Changes in heat distribution in the working chamber of a simple solar water heater with a reflector and a tubular system at different points in time.

DISCUSSION

The tubular system, by providing water flow, also increases the heat transfer surface and ensures uniform temperature distribution. It was observed that at higher water flow rates in the system (in the range of 1.0–1.5 m/s), the convective heat transfer coefficient increases significantly. This improved internal water circulation and contributed to a more uniform heat distribution [30-32]. At lower flow rates (0.5 m/s), heat transfer occurred relatively more slowly, and a decrease in efficiency was observed. Based on these results, improving the design of the working chamber and optimizing the placement of reflectors can help increase the overall system efficiency. Observations taken at different times indicate the need to manage the heat transfer process according to the water flow rate. Thus, these systems can be further optimized to enhance internal heat transfer and overall energy efficiency.

CONCLUSION

The heat transfer process in the working chamber of a simple tank-type solar water heater with a reflector and tubular system depends on the intensity of solar radiation. The reflectors and tubular system play a crucial role in collecting solar energy and transferring it to the water as heat. In this system, the temperature distribution and uniformity of heat are determined by measurements taken at different times.The heat transfer process ensures changes in temperature according to the water flow rate and solar radiation intensity, which allows for an increase in system efficiency. As a result, the temperature distribution over time and the overall efficiency of the system are optimized. The obtained results are summarized below. Based on the findings, improving the design of the working chamber, optimizing the placement of reflectors, and incorporating a tubular system can enhance the overall efficiency of the solar water heater. Observations made at different times indicate the need to control the heat transfer process according to the water flow rate.

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