E3S Web of Conferences **498**, 01013 (2024) https://doi.org/10.1051/e3sconf/202449801013
ICAPE2024

CFD analysis for absorber tube of a solar water heater collector

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Abstract. In this work, CFD analysis of smooth absorber fin tube and screw absorber fin tube used in solar water heater collector is considered and compared. Three-dimensional numerical CFD model simulations were performed using flow simulation in COMSOL Multiphysics software. A flat absorber wing tube made of different materials (Stainless steel, Iron, Copper, Aluminum) is evaluated. At the same time, different water inlet velocities were tested. Various velocities such as 0.01 m/s, 0.02 m/s, 0.025 m/s, 0.035 m/s have been simulated and here the inlet velocity of 0.2 m/s is close to optimal for the given size, the outlet velocity at this velocity is suitable for direct consumption.

1 Introduction

Renewable energy sources serve a dual purpose by not only enhancing environmental conditions but also addressing the growing need for clean energy. Solar energy, in particular, has witnessed a rising trend in its utilization in recent years, attributed to its abundant availability and substantial potential [1]. Solar energy can meet the energy needs of the world using a few percent of uninhabited areas [2-3]. In a prior study, it was found that around 40% of the global energy production is dedicated to heating purposes [4]. The research also revealed the versatility of solar energy conversion, exemplified by the utilization of solar water heaters (SWH) that transform solar energy into heat through radiation for various applications. The efficacy of both the SWH and the collector hinges significantly on the generation of heat from solar sources using solar collectors. Additionally, SWH contributes to 63% of domestic hot water systems, 28% for various other purposes, and the remaining 9% for activities such as pool heating, solar district heating, and space heating [5].

Passive systems commonly employ flat-plate collectors (FPC) due to their cost-effectiveness and straightforward technology, typically applied in the temperature range of 40°C to 60°C [6-7]. Over time, numerous studies have explored FPC, focusing on modifications in its geometry, the integration of nanofluids, the incorporation of heat pipes, vacuum collectors, and the application of solar-selective coatings [8]. For instance, Touaba et al. developed an FPC that attained an average energy efficiency of 64% by incorporating waste oil fluid and employing sun tracker control to maintain a consistent radiation value [9]. However, the fluid produced cannot be directly used for activities like warm baths or

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household needs. Other studies utilizing water fluid have reported lower efficiency and higher output temperatures. To tackle this challenge, a novel FPC was devised, featuring a double-ducted cellular polygal cover, which demonstrated increased efficiency, although it resulted in a persistently high-water consumption rate [10].

Modern solar water heater collectors are available. High thermal efficiency can be obtained from the aforementioned vacuum or PCM collectors, but they are expensive. For example, we can see the prices of this type of SWHC ranging from $248 to $1200 and even higher [11-13]. It requires an additional price for transportation, installation and service, even reaching $3,600 on average [13]. According to the latest poverty statistics, approximately 9.2% of the global population, or about 700 million people, live in extreme poverty. Extreme poverty is defined as living on less than $1.90 per day. This population is largely concentrated in developing countries, with about 90% of people living in extreme poverty residing in sub-Saharan Africa and South Asia [14]. And these countries are sunny countries, taking into account all of the above, solar water heater collectors are simple and cheap to make, and at the same time, they require improvement. This manuscript is one of the first steps to address the shortcomings identified in the above works. Different materials were evaluated in the first step to make the most cost-effective SWH collectors, while at different water inlet velocities [15-27].

2 Materials and methods

SWH collectors are mainly used in the systems shown in Figure 1, while Figure 2 shows a view of a flat SWH collector and Table 2 shows the geometric constants and physical parameters. According to the performed investigation, the flow inside the pipe is laminar. Three-dimensional numerical simulations were performed in the COMSOL Multiphysics program at Laminar flow, turbulent flow, Heat transfer in solid and fluids physics interfaces, and the FEM (finite element method) method was chosen for the solution. A stream of water at a temperature of 20 ^{0}C enters the pipe at different velocities, i.e. 0.01 m/s, 0.02 m/s, 0.025 m/s and 0.035 m/s. Velocity–inlet and pressure–outlet boundary conditions were considered at the inlet and outlet ports, respectively. To verify the simulation, a heat flux of 1000 W/m^2 was applied to the surface of the SWH flat part. In addition, the thermo-physical properties of the pipe material and fluid are shown in Table 1.

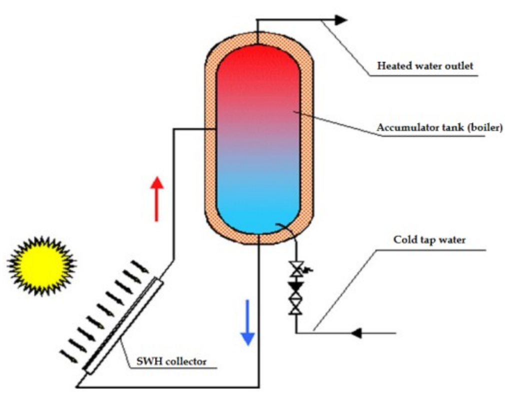

Fig.1. Diagram of a solar water heater system.

Solar water heaters consist of a solar collector, storage tank, heat exchanger, cold water inlet, hot water outlet, and circulation pump. The collector captures sunlight, heating a fluid which is circulated to the storage tank via the heat exchanger. Cold water enters the tank, gets heated, and is pumped out as hot water for household use. These systems are cost-effective, especially in sunny areas, reducing reliance on fossil fuels and saving on energy bills (Figure 1).

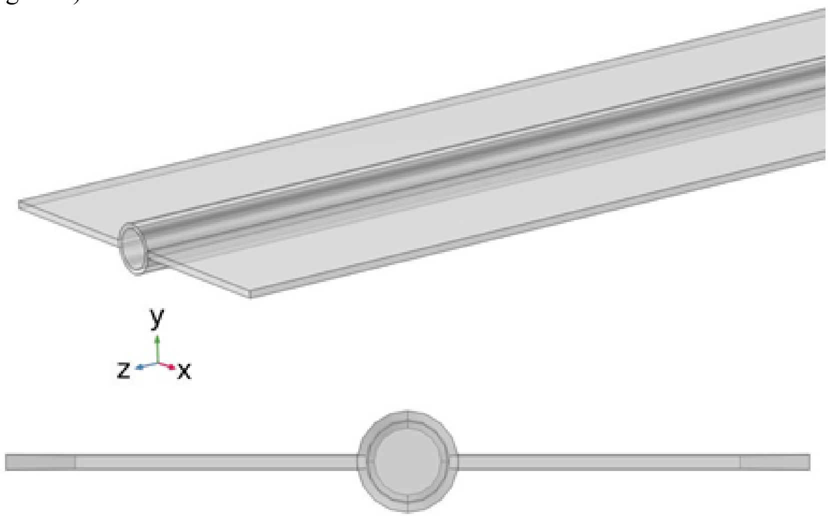

Fig. 2. SWH flat collector absorber fins tube geometric view.

In this work, a finned heat-receiving tube (fins) made of four different materials was investigated. Materials such as Steel AISI 4340, Iron, Aluminum, Copper listed in table 1 were subjected to numerical results at different speeds and the best one was selected. The boundary conditions are also listed in table 2.

Table 1. The thermophysical properties of materials.

Fluid	Pipe				Property
Water	**Steel AISI**	**Iron**	**Aluminum**	**Copper**	
4200	475	440	900	385	Heat capacity at constant pressure [J/(kg·K)]
1000	7850	7870	2700	8960	Density [kg/m³]
0.6	44.5	76.2	238	400	Thermal conductivity [W/(m·K)]
210e-6	12.3e-6	12.2e-6	23e-6	17e-6	Coefficient of thermal expansion [1/K]
4.18	0.48	0.45	0.9	0.39	Ratio of specific heats [kJ/(g·K)]

Table 2. Physical parameters of the analyzed absorber tube for SWH collector.

Parameters		Value
Diameter of inner the tube	D_1	8 mm
Diameter of outer the tube	D_2	10 mm
Length of the tube	L	750 mm
Height of the fins	H	2 mm
Length of the fins	l	35 mm
Inlet velocity	u	$0.01, 0.02, 0.025, 0.035\ \mathrm{m \cdot s^{-1}}$
Solar radiation	I	$1000\ \mathrm{W \cdot m^{-2}}$
Ambient temperature	T_{amb}	298.15 K
Inlet temperature of the water	T_{inlet}	298.15 K

3 Results and Discussions

In this section, the effect of different materials on thermal efficiency is investigated numerically. Four different materials were examined and the obtained results were compared. The materials considered here were investigated only at different flow rates, the model is shown in Figure 2. Thermophysical indicators for these materials and water are presented in table 1. The geometric dimensions and physical dimensions of the model are shown in Table 2. Thus, as a result of the examination of materials such as Steel, Iron, Copper, Aluminum, it was found that the surface of copper is less heated (Figure 3), at the same time, it shows that the temperature of water exit is higher in copper compared to other materials (Figure 4).

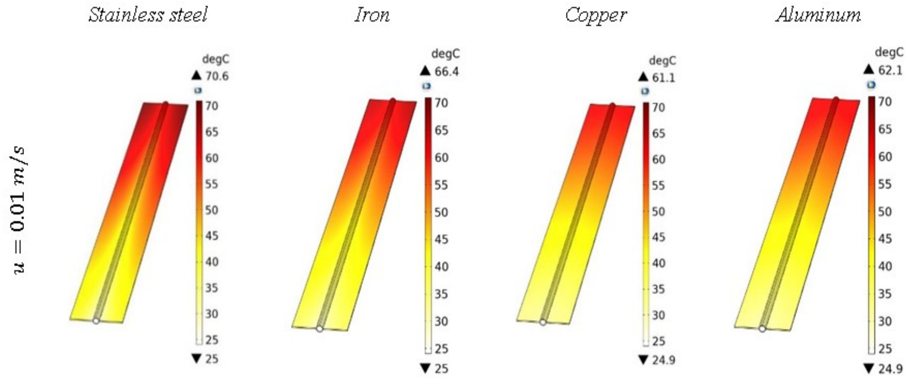

Fig. 3. Surface temperatures of receiver tubes with different materials.

Figure 3 presents only the water tested image with a flow inlet velocity of 0.01 m/s. In this case, we can see that the stainless-steel material heats up to a temperature of 25 ^{0}C around the inlet and wings, and up to 70.6 ^{0}C around the outlet. These results are presented in Figure 4(a) for different flow rates. When the iron material was examined for water with an inlet flow velocity of 0.01 m/s, it was found that the temperature changed from 25 ^{0}C to 66.4 ^{0}C, and at the same velocities, it was found that Copper heated from 25 ^{0}C to 61.1 ^{0}C, and Aluminum from 25 ^{0}C to 62.1 ^{0}C. These results are presented in detail in Figures 4(b), 4(c), 4(d) (Figures 4 and 5).

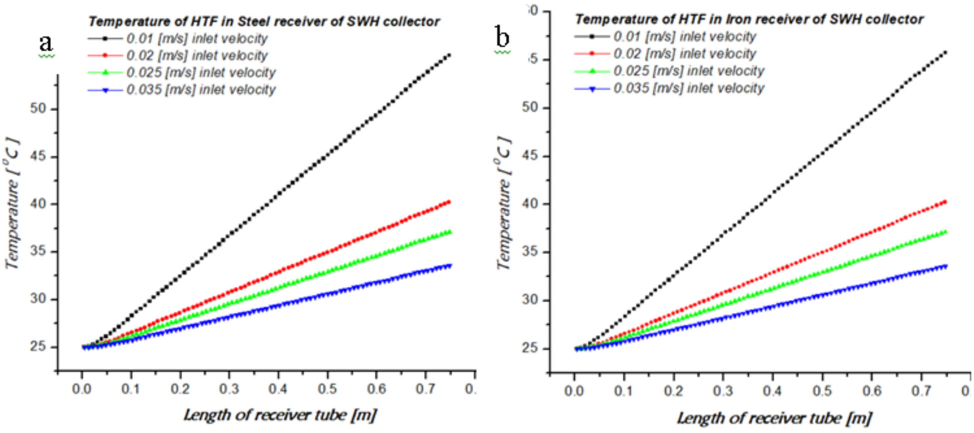

Fig. 4. Temperature variation of HTF with the length of receiver made of various materials.

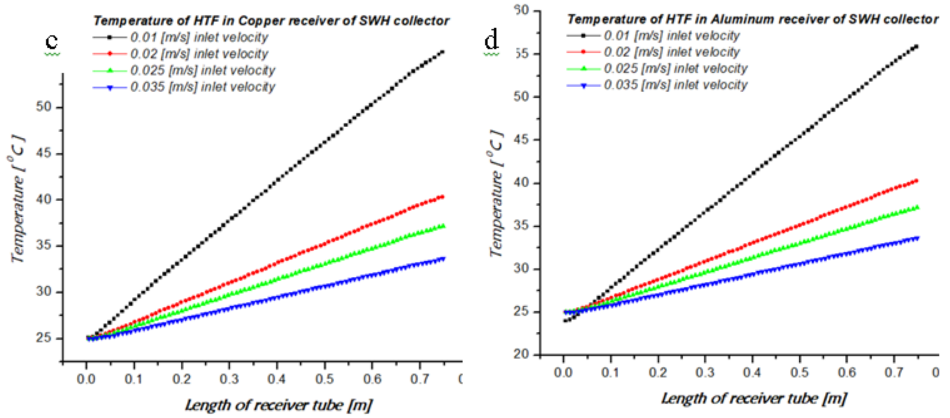

Fig. 5. Temperature variation of HTF with the length of receiver made of various materials.

For Heat Transfer in Solids.

Following equation is utilized for solving the Heat Transfer in Solids Interface.

$$\rho C_p \left(\frac{\partial \mathrm{T}}{\partial t} + \boldsymbol{u}_{trans} \cdot \nabla \mathrm{T}\right) + \nabla \cdot (\boldsymbol{q} + \boldsymbol{q}_r) = -\alpha \mathrm{T}\colon \frac{dS}{dt} + Q \tag{1}$$

Where, ρ is the density (kg/m^3), C_p is the specific heat capacity at constant stress (J/(kg·K)), T is the absolute temperature (K), u_{trans} is the velocity vector of translational motion (m/s), q is the heat flux by conduction (W/m^2), q_r is the heat flux by radiation (W/m^2), α is the coefficient of thermal expansion (1/K), S is the second Piola-Kirchhoff stress tensor (Pa), Q contains additional heat sources (W/m^3).

For Heat Transfer in Fluids.

The Heat Transfer in Fluids Interface solves for the following equation

$$\rho \rho \mathrm{Cp} \left(\frac{\partial \mathrm{T}}{\partial t} u \cdot \nabla \mathrm{T}\right) + \nabla \cdot (q + q_r) = \alpha_p \mathrm{T} \left(\frac{dp}{dt} + u \cdot \nabla_p\right) + \tau\colon \nabla u + Q \tag{2}$$

The Cauchy stress tensor, σ, is split into static and deviatoric parts as in:

$$\sigma = -pI + \tau \tag{3}$$

For ideal gases, the thermal expansion coefficient takes the simpler form $\alpha_p = 1 / T$.

$$\alpha_P = \frac{1 \partial \rho}{\rho \partial T} \tag{4}$$

For a steady-state problem, the temperature does not change with time and the terms with time derivatives disappear. The first term of the right-hand side of equation 12 is the work done by pressure changes and is the result of heating under adiabatic compression as well as some thermoacoustic effects. It is generally small for low Mach number flows.

$$Q_P = \alpha_P \mathrm{T} \left(\frac{dp}{dt} + u \cdot \nabla_p\right) \tag{5}$$

The second term represents viscous dissipation in the fluid:

$$Q_{vd} = \tau : \nabla u \quad (6)$$

Where, ρ is the density (kg/m^3), C_p is the specific heat capacity at constant stress (J/(kg·K)), T is the absolute temperature (K), u_{trans} is the velocity vector of translational motion (m/s), q is the heat flux by conduction (W/m^2), q_r is the heat flux by radiation (W/m^2), α is the coefficient of thermal expansion (1/K), S is the second Piola-Kirchhoff stress tensor (Pa), Q contains additional heat sources (W/m^3).

4 Conclusions

In this research work, 4 different types of materials (Stainless steel, Iron, Copper, Aluminum) were investigated for solar flat water heating collector. During the simulation, the solar radiation at 1000 W/m^2 was given the same to all models, while the ambient temperature was 298.15 K and the inlet water was also taken as 298.15 K. All models were tested at 4 different water inlet flow velocities (0.01 m/s, 0.02 m/s, 0.025 m/s, 0.035 m/s). As a result, it was found that copper is the material with the least surface heat among them. According to the Stefan-Boltzmann law, when the surface temperature is low, radiation heat loss decreases, i.e. $Q_{rad} \sim T_{surf}^4$, when the temperature decreases, the energy lost decreases to its 4th degree. Since solar water heating collectors serve for a long time, even if the temperature difference between the surfaces of the materials is small, copper is considered superior. At the same time, the water heats up better due to the reduction of lost energy.

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