

Computational Study of a Spiral Pipe Collector for Solar Water Heating System

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Abstract. The water-heating system is considered one of the largest energy consumers in the commercial building sector. The advancement of water heating systems powered by renewable energy sources has become pivotal. The low cost and ease of maintenance of solar collectors for water heating systems have already made them popular for both residential and commercial applications. Therefore, the present study focused on an innovative design of a domestic water heater system. The system consists of a solar collector with a selective, black-nickel-coated spiral pipe and a storage tank. Selective coating can increase the thermal efficiency of the collector. Temperature variations, useful energy gains, and the efficiency of a solar water heater are analysed numerically. The discussion section of this article provides detailed demonstrations of these key parameters.

1 Introduction

Solar energy is considered one of the most promising and viable forms of renewable energy due to its widespread geographic distribution [1]. Solar thermal collectors are among the most efficient ways to capture solar energy, satisfying rising demand while also helping reduce greenhouse gas emissions. [2-5]. A solar collector is, in general, a thermal energy device that absorbs sunlight and converts it into useful thermal energy. These systems typically operate by circulating a heat transfer fluid, which serves as a medium for energy transfer as it flows through the collector's tubes and absorbs incident solar radiation [6].

The Thermal efficiency of a solar collector is influenced by various parameters. Key factors include the positioning of the collector plate, the nature and composition of the coating applied to it, the characteristics of the glazing material, the riser tubes in proportion to their diameter, the flow rate of the working fluid, the intensity of incoming solar radiation, and the thickness of the insulation applied to the bottom and sides of the collector [7]. Design modification is a fundamental technique that results in significant variation in other parameters to ensure system compatibility.

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The experimental study conducted by M. Moravej et al. evaluates a circular flat-plate solar collector with spiral tubes, demonstrating improved efficiency (up to 75.3%) compared to conventional designs due to secondary flow effects. It highlights the positive impact of increased flow rate and solar radiation on performance, offering a simple and effective design enhancement for solar water heaters [8]. Another study by Mohamad and Mohd Shaifudeen (2024) examines a flat-plate solar water heater using hollow PV-C tubes in a novel rectangular spiral inward–outward alternating-flow pattern. Despite lower thermal conductivity, the system achieved a water temperature of 64°C and an efficiency of 23.94%, demonstrating that the polymer absorber could be a cost-effective alternative to metal absorbers for household solar water heaters [9].

To further enhance the understanding of the thermal performance and efficiency of spiral tube solar water heaters, CFD modelling can be used to evaluate fluid flow behavior, heat transfer, and temperature distribution within the system. In particular, this approach can offer valuable insights into optimising the design of solar water heaters with different innovative collector configurations, ensuring more accurate predictions of system behaviour under varying operating conditions.

The combined impact of spiral tube geometry and selective absorber coating using sophisticated numerical modeling has received little attention despite the numerous studies on flat-plate and spiral tube solar collectors that have been published. In order to close this gap, the current study combines a thorough CFD-based analysis with a black-nickel selectively coated spiral tube absorber. In contrast to earlier research, the thermal behavior, fluid dynamics, and useful energy gain are assessed concurrently at different inlet velocities. This method offers a solid framework for optimizing home solar water heater designs and a deeper comprehension of the coupled heat transfer mechanisms.

2 Materials and methods

2.1 Finite Element Analysis

Finite element analysis was used to solve the two-dimensional Navier-Stokes equations with the energy equation in COMSOL Multiphysics. Engineering and scientific research use the numerical computational technique known as finite element analysis (FEM) to model and analyse complicated physical processes. Differential equations are frequently solved using FEM, which also helps to analyse environments with complicated geometries.

The 3D model of the spiral tube solar collector is built. Geometrical views are provided in Fig. 1. The dimension of the rectangular shape side of collector 1×1 m, outer diameter of spiral tube is 0.01 m, and inner diameter is 0.0075 m. Simulations are conducted without considering the water storage medium. The generated mesh for computational domains is given in Fig. 1

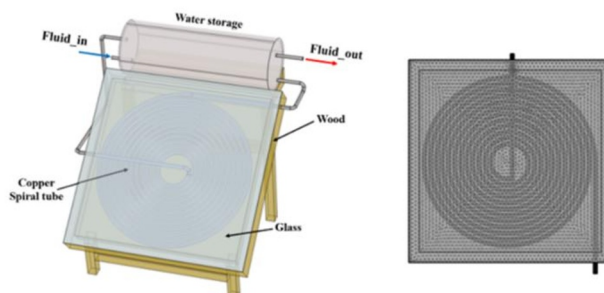


Fig. 1. Geometric view of spiral tube solar collector and generated mesh for computational domains.

Table 1. Thermophysical properties of materials [10, 11].

№	Materials	Density (kg/m ³)	Specific heat (J/kg·K)	Thermal conductivity (W/m·K)
1	Water	998.2	4280	0.6
2	Copper	8960	390	401
3	Stainless steel	7850	420	25
4	Air	1.293	1000	0.026

Thermophysical properties of materials are given in Table 1. Water is used as a heat transfer fluid [11], glass is chosen for the cover, copper is utilised for the spiral tube material, and air is used as the medium between the glass cover and the copper tubes. The Glass cover significantly reduces the radiative heat losses to the environment. Copper has better conductivity than other materials such as aluminium, stainless steel, and iron. The collector is covered with stainless steel because this material has low thermal conductivity, reducing heat loss to the surroundings. Natural conveyance and weak compressibility are considered at all boundaries. The collector surface receives approximately 800 W/m² of solar radiation. Different inlet velocities (0.02, 0.04, 0.06, 0.08 m/s) were selected. Initial and inlet temperatures were 293.15 K and 298.15 K, respectively. Solar radiation is considered as constant at around 800 W/m² and it was applied to half of the spiral tube and the upper surface of the collector.

In order to simulate a typical operating period with stable solar irradiance, the simulations were carried out under steady-state conditions. In solar thermal studies, solar radiation was assumed to be constant at 800 W/m², which corresponds to typical clear-sky conditions. Because of the low inlet velocities and corresponding Reynolds numbers, the flow inside the spiral tube was regarded as laminar. In order to separate and evaluate the spiral tube collector's intrinsic heat transfer performance, thermal interaction with the storage tank was disregarded.

Table 2. Elements for the finite element solver.

Elements type	Domain elements	Tetrahedra	Prism	Edge elements
	2743403	2206119	537284	47754

3 Transfer heat from one solid or liquid to another

This study modelled heat transfer in both solid and fluid domains using the Heat Transfer interfaces in COMSOL Multiphysics, which are founded on the principle of energy conservation and established formulations documented in the literature [10]. The model takes into account both conductive heat transfer in solid parts and convective–conductive heat transfer in the fluid that flows through the spiral tube.

Thermal conduction within the absorber plate and tube walls is the main way that heat transfer through solid areas. Thermoelastic effects were also used to show how thermal and mechanical responses of materials interact. In steady-state conditions, temporal temperature fluctuations were disregarded, enabling the analysis to concentrate on spatial temperature distributions.

For the fluid domain, heat transfer was modeled by taking into account thermal convection, diffusion, pressure-related thermal work, and viscous dissipation. Because the flow regime had a low Mach number, pressure-related effects were small. The steady-state assumption facilitated an effective assessment of the integrated thermal–fluid dynamics of the spiral pipe solar collector system [10].

4 Results and discussion

For modeling, COMSOL Multiphysics' laminar flow interfaces are used for heat transfer in solid and fluid environments. The simulation is conducted under a stationary solver configuration. Surface temperature variation of the spiral tube is demonstrated in Fig. 2. The maximum surface temperature distribution is observed at lower inlet velocities, indicating a more pronounced thermal gradient under reduced flow conditions. At 0.02 m/s, the highest surface temperature was 356 K.

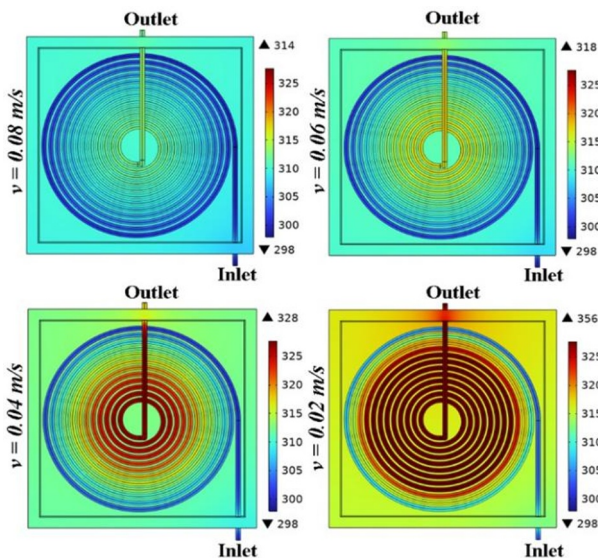


Fig. 2. Surface temperature distribution of spiral tube collector at four different velocities.

4.1 Model validation

The obtained results were qualitatively validated against published experimental and numerical studies in order to confirm the dependability of the developed numerical model.

According to Moravej et al. [8], spiral tube flat-plate collectors have higher surface temperatures and improved heat transfer at lower flow velocities because of longer residence times. This is in line with the current results, which show that the maximum surface temperature of 356 K was recorded at 0.02 m/s. In a similar vein, the temperature rise trends with increasing inlet velocity are in good agreement with the findings of Mohamad and Mohd Shaifudeen [9], who found that higher flow rates improved convective heat transfer while lowering outlet temperatures. These recurring patterns attest to the developed CFD model's accuracy in capturing the hydrodynamic and thermal behavior of spiral tube solar collectors.

4.2 Numerical simulation

The fluid's temperature change at four distinct speeds, according to the length of the outlet tube of the spiral pipe collector, is illustrated in Fig. 3. Maximum fluid temperature variation was observed at about 354.5 K at 0.02 m/s velocity, while minimum temperature variation was obtained with 0.08 m/s velocity at around 312.17 K. The outlet temperature decreased slightly due to natural convection across all boundaries.

All thermophysical properties of the spiral pipe collector at four different velocities are evaluated by inserting mathematical expressions into the COMSOL Multiphysics variable Fig 4 demonstrates the velocity and pressure variation of fluid along with the outlet tube of the spiral pipe collector.

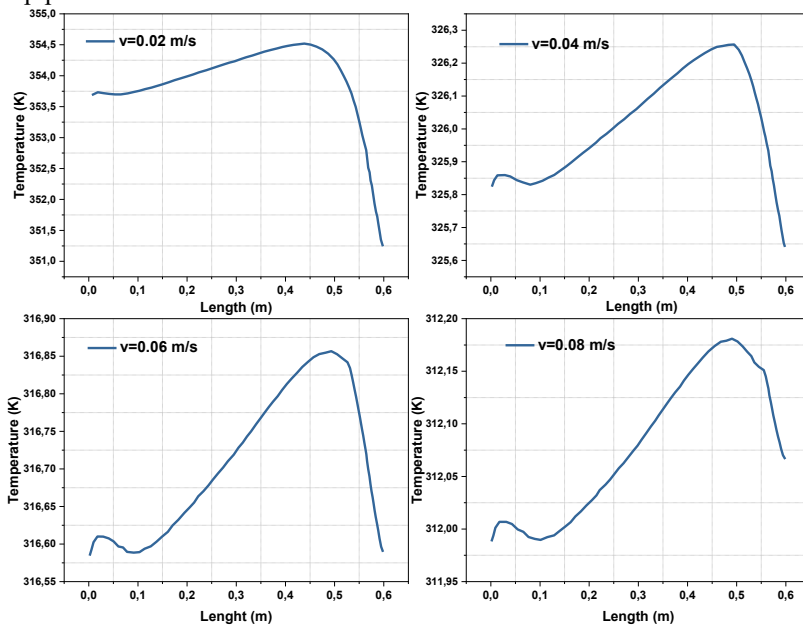


Fig. 3. Temperature variations of fluid along with the outlet tube of the spiral pipe collector at four different velocities.

All thermophysical properties of the spiral pipe collector at four different velocities are evaluated by inserting mathematical expressions into the variable part of COMSOL Multiphysics. Fig. 4 demonstrates the velocity and pressure variation of fluid along with the outlet tube of the spiral pipe collector.

The heat transfer coefficient is a critical parameter that governs the rate of thermal energy exchange between the fluid and the absorber surface, significantly influencing the overall thermal performance of the spiral pipe solar collector.

Heat transfer coefficients at four different velocities, depending on the length of the outlet tube of the spiral pipe collector, are shown in Fig. 5.

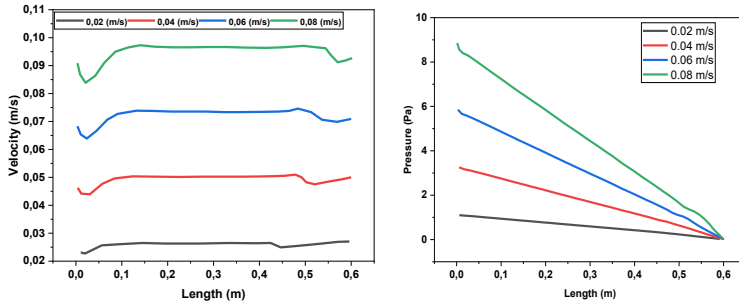


Fig. 4. Variations of velocity and pressure at four different velocities.

The heat transfer coefficient is a critical parameter that governs the rate of thermal energy exchange the fluid's distance from the absorber surface, significantly influencing the overall thermal efficiency of the spiral pipe solar collector. Heat transfer coefficients at four different velocities, depending on the length of the outlet tube of the spiral pipe collector, are shown in Fig. 5. Useful energy (Q_u) represents the amount of individual energy that the collector absorbs and transports to the head transfer fluid (HFT) by considering the heat losses. Useful energy gain through the spiral pipe collector at four different velocities is shown in Fig. 6. Useful energy gain was approximately 8.2 W when the inlet velocity of HTF increased.

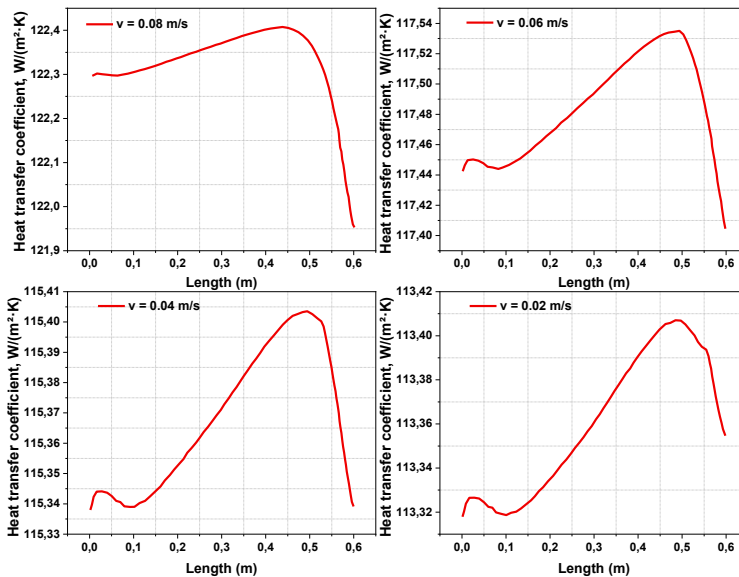


Fig. 5. Variation of heat transfer coefficients through spiral pipe collector at four different velocities.

The amount of solar energy absorbed by the collector and transferred to the heat transfer fluid (HF) while accounting for heat losses is known as useful energy (Q_u). Useful energy gain through the spiral pipe collector at four different velocities is shown in Fig. 6. Useful energy gain was approximately 8.2 W when the inlet velocity of HTF increased.

The solar collector's useful energy gain (Q_u), which can be expressed as follows, was determined using the temperature differential between the heat transfer fluid's inlet and outlet.

$$Q_u = \dot{m}c_p(T_{out} - T_{in}) \quad (1)$$

where T_{in} and T_{out} are the inlet and outlet temperatures, respectively, c_p is the water's specific heat capacity, and \dot{m} is the mass flow rate. Despite a lower outlet temperature, a higher useful energy gain results from an increase in mass flow rate due to an increase in inlet velocity.

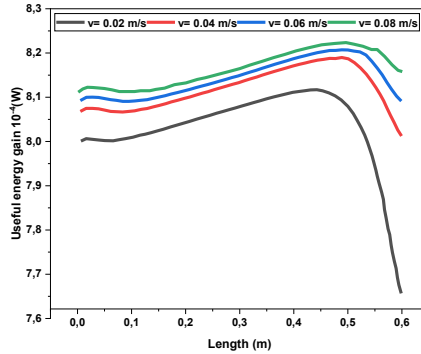


Fig. 6. Variation of useful energy gain through spiral pipe collector at four different velocities.

Variation of Reynolds Cell and Prandtl numbers according to the length of the outlet tube of the spiral pipe collector is given in Fig. 7. As can be seen, an inlet velocity of 0.08 m/s results in the highest Reynolds cell (Re) and Prandtl (Pr) values. By applying a lower value for inlet velocity, these properties decrease considerably. Reynolds and Prandtl numbers are crucial for determining the Nusselt (Nu) number. Convective heat transfer coefficient depends on the Nusselt number. Therefore, to demonstrate the heat transfer coefficient, we analyzed Reynold, Prandtl, and Nusselt numbers.

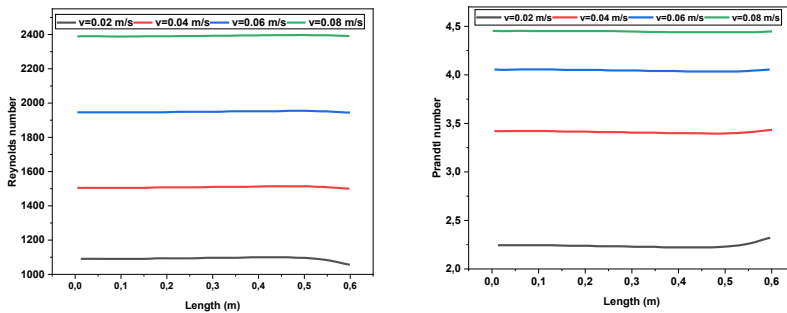


Fig. 7. Variations of Re and Pr numbers at four different velocities.

Increased inertial forces and better thermal diffusion properties within the flow are indicated by the observed rise in Re and Pr numbers with higher inlet velocities. The Nu number, which controls the convective heat transfer coefficient, is directly impacted by these dimensionless numbers. Additionally, secondary flow structures created by the spiral tube geometry enhance fluid mixing, decrease the thickness of the thermal boundary layer, and encourage more consistent heat transfer along the absorber surface.

5 Conclusion

In this article, a numerical model of a spiral pipe collector is investigated. gain and fluid flow behaviour within the spiral pipe. Temperature distribution, convective heat transfer coefficient, and useful energy collector are evaluated at 0.02, 0.04, 0.06, 0.08 m/s velocities.

Higher temperature variations are observed at lower inlet velocities. Maximum Reynolds numbers, Prandtl numbers, and useful energies are noticed with higher inlet velocities. Spiral pipe configuration also promotes secondary flow effects, contributing to improved heat distribution and enhancing the thermal efficiency of flat-plate solar collectors. These numerical techniques serve as a foundation for further studies to optimise design parameters and incorporate advanced materials to enhance performance.

The study's conclusions show that spiral tube solar collectors with selective absorber coatings have a lot of potential for use in home water heating systems. The numerical results verify that thermal efficiency and useful energy gain can be balanced by choosing the right inlet velocity. Future experimental and industrial-scale implementations can benefit greatly from the developed CFD framework's ability to optimize collector geometry, coating materials, and operating conditions.

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