CFD Analysis of Thermal Performance in a U-Tube Solar Collector

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Abstract. Solar water heating systems have both domestic and industrial applications that are both inexpensive and easy to maintain. In this study, the thermal performance of a U tube evacuated tube solar collector (ETSC's) was evaluated numerically. A numerical model illustrates temperature distributions, convective heat transfer coefficients, useful energy gains, and fluid flow characteristics within the U tube of the collector at steady-state, solar heating conditions. The modelling technique generates useful design optimization information for evacuated tube solar collectors and contributes to the ongoing efforts to create more efficient applications for solar thermal energy.

1 Introduction

Solar power is extensively acknowledged as one of the most promising and viable forms of renewable energy because of its widespread geographical availability. Among the various methods for harnessing solar energy, solar thermal collectors are particularly efficient in meeting growing demands while assisting to the mitigating of greenhouse gas emission [1-3]. In general, a solar thermal energy device designed to capture radiation by absorbing sunlight and converting it into usable thermal energy. These systems typically operate through the circulation of heat transfer fluid, which functions as a medium for energy transfer by flowing through the collector's tubes and absorbing incident solar radiation [4].

Currently, glass evacuated tubes are recognized as a critical element in solar thermal energy systems, particularly due to their capacity to achieve higher operating temperatures with minimal heat loss. This thermal advantage makes them suitable for residential application. Multiple design configurations, of evacuated tube solar collectors, including U-tube, H-tube, T-tube have been engineered to support diverse solar thermal energy applications, with each configuration tailored to optimize thermal performance and meet

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specific operational requirements [5]. As a result, evacuated tube solar collectors such as heat pipe and U-tube configurations are extensively employed for domestic hot water production and space heating purposes. U-tube glass evacuated tube solar collector is considered to be more commonly implemented compared to heat pipe [6].

This study presents a computational fluid dynamics (CFD) that evaluate the thermal performance of an evacuated U-tube solar collector. By modelling heat transfer and fluid flow inside the collector using finite element methods, the research aims to evaluate temperature fluctuations, coefficient of heat transfer and thermal behaviour under varying operational conditions. The findings provide information about the impact of design parameters and flow dynamics on energy capture efficiency, thereby supporting the optimization of U-tube solar collector systems for improved thermal performance.

2 Materials and methods

2.1 Analysis of Finite Element

The finite element method was used in order to calculate numerically the two-dimensional Navier-Stokes equations and heat transfer equations using the COMSOL Multiphysics software package [7-9]. Finite element analysis (FEM) is widely used for performing numerical simulations on engineering or scientific problems and allows the modelling and analysis of complex physical processes using the principles of finite element theory. FEM is often employed in determining an approximate solution of a partial-differential (PDE) or an ordinary differential equation (ODE) when the geometry of the problem is too complicated.

The 3D model of U-tube is built. Geometrical dimensions are provided in the Figure 1. The length of U-tube is 500 mm, outer diameter of U-tubes are 7.94 mm, the diameter of vacuum domain is 34 mm, outer diameter of glass cover is 44 mm.

Table 1. Materials' thermophysical characteristics [10].

№	Materials	Density (kg/m^3)	Heat capacity $(J/kg \cdot K)$	Heat conductivity $(W/m \cdot K)$
1	Water	998.2	4280	0.6
2	Copper	8960	390	401
3	Air	1.293	1000	0.026

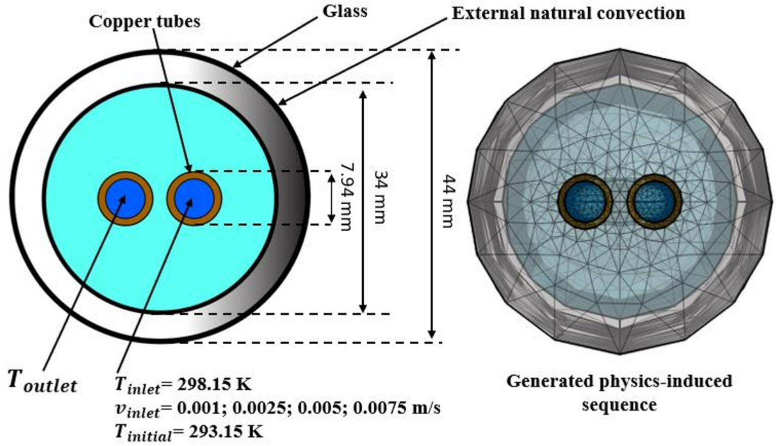

Fig. 1. U-tube and generated mesh in two-dimensional geometric view.

Materials' thermophysical characteristics are given in the Table 1. For heat transfer fluid water is selected, glass is chosen for cover, copper is utilized for U-tube material, Air is considered to be vacuum medium between glass cover and copper tubes. Glass cover significantly reduces the radiative heat loses to the environment. Copper has better conductivity when compared to the other materials like aluminium, stainless steel and iron. All materials listed in Table 1 have specific boundary conditions. The water enters at velocity (Vin) and temperature (Tin) as shown in the accompanying Figure 1. Weakly compressible flow and natural convection from all boundaries are both taken into account. Solar radiation is assumed to be constant at approximately 800 W/m2 and acts on one-half of the u-tubes.

Table 2. Elements number for finite element solver.

Elements type	Domain elements	Tetrahedron	Prism
	257872	188328	69544

2.2 Regarding Heat Transmission in Solids

The following formula is used to solve the Heat Transfer in Solids Interface problem.

$$\rho C_p\left(\frac{\partial T}{\partial t}+u_{trans}\cdot\nabla T\right)+\nabla\cdot(q+q_r)=-\alpha T{:}\frac{dS}{dt}Q \qquad (1)$$

In a steady-state problem, the temperature remains constant over time, and the time derivatives of the terms vanish.

Thermoelastic damping, the first term on the right-hand side of equation 1, takes into consideration thermoelastic effects in solids:

$$Q_{ted}=-\alpha T{:}\frac{dS}{dt} \qquad (2)$$

Note that, according to the Time Derivative subsection of Material and Spatial Frames, the d/dt operator is the material derivative [11].

2.3 For Heat Transfer in Fluids

The following equation can be solved using the Heat Transfer in Fluids Interface:

$$\rho Cp\left(\frac{\partial T}{\partial t}u\cdot\nabla T\right)+\nabla\cdot(q+q_r)=\alpha_p T\left(\frac{dp}{dt}+u\cdot\nabla_p\right)+\tau:\nabla u+Q \quad (3)$$

The Cauchy stress tensor, σ, is divided into static and deviatoric components.

$$\sigma=-pI+\tau \quad (4)$$

The thermal expansion coefficient for ideal gases takes the simpler form $\alpha_p = 1/T$

$$\alpha_P=\frac{1\partial\rho}{\rho\partial T} \quad (5)$$

In a steady-state problem, the temperature remains constant over time, and the time-dependent terms vanish. Heating under adiabatic compression and certain thermoacoustic effects result in the first term on the right-hand side of equation 12, which represents the work done by pressure changes. For flows with a low Mach number, it is typically small.

$$Q_P=\alpha_P T\left(\frac{dp}{dt}+u\cdot\nabla_p\right) \quad (6)$$

The fluid's viscous dissipation is represented by the second term.

$$Q_{vd}=\tau:\nabla u \quad (7)$$

These equations above are available in the literature [12]

3 Results and discussion

The simulation is conducted under stationary solver configuration. Surface temperature variation of U-tube is demonstrated in the Figure 2. Temperature at the outlet of U-tube is increased significantly when inlet velocity of fluid decreased.

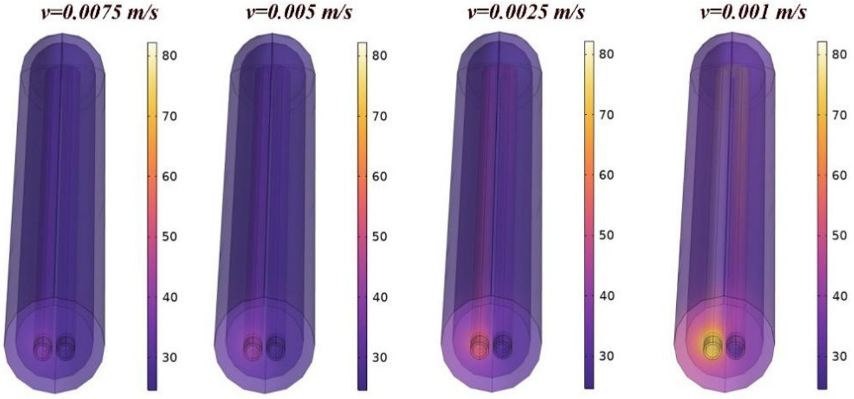

Fig. 2. Surface temperature of U-tube at four different velocities.

Temperature variation of fluid and heat transfer coefficients at 4 various velocities with the length of U-tube is illustrated in the Figure 3. Maximum fluid temperature variation and heat transfer coefficient were observed at 0.001 m/s velocity. The lowest temperature variation and heat transfer coefficient were obtained with 0.0075 m/s velocity.

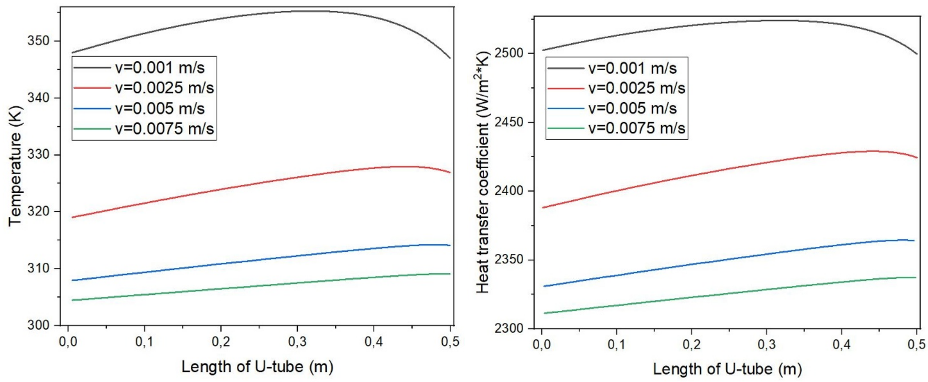

Fig. 3. Temperature variations and heat transfer coefficients of fluid at various velocities.

All thermophysical properties of U-tube are analysed by applying mathematical expressions to the variable parameters of COMSOL. Variation of Reynold Cell and Prandtl numbers according to the length of U-tube are illustrated in the Figure 4. As it can be seen that maximum Reynold Cell and Prandtl values are observed with 0.0075 m/s inlet velocity of the fluid. By applying lower value for inlet velocity, these properties decrease considerable. Reynold and Prandtl numbers are necessary to find out Nusselt numbers. heat transfer coefficient is depended on the Nusselt number. Therefore, to find out the heat transfer coefficient, we analysed Reynold, Prandtl, Nusselt numbers.

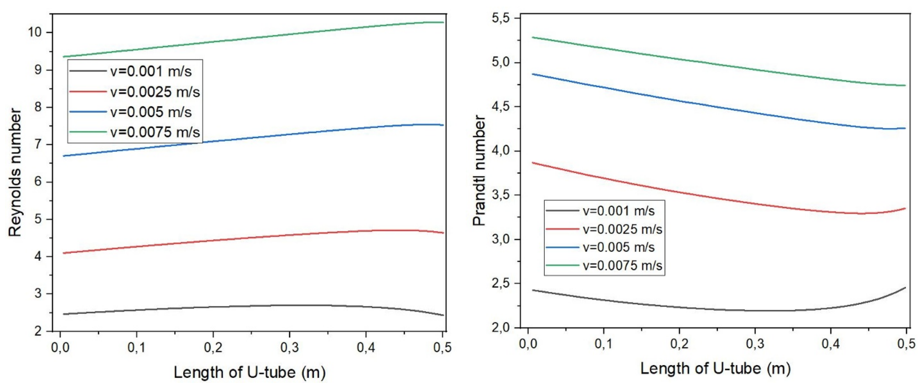

Fig. 4. Temperature variations and heat transfer coefficients of fluid at four different velocities.

Useful energy (Qu) indicates how much solar energy the collector has absorbed and transferred to the heat transfer fluid (HFT) by considering the heat losses. Useful energy gain through the U-tube at four various flow rates is demonstrated in the Figure 5. Useful energy gain is observed higher when the inlet velocity of HTF increase.

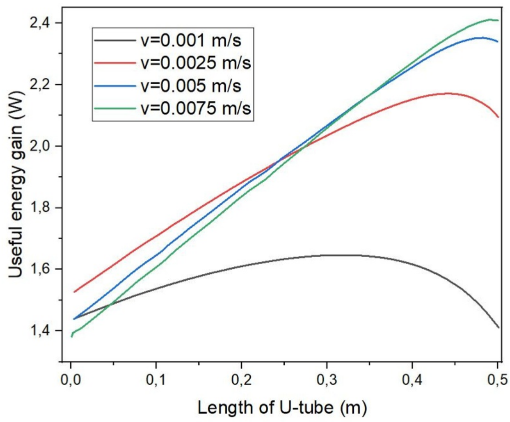

Fig. 5. Changes in the useful energy gain through U-tube at 4 various velocities.

4 Conclusion

This article analyses a numerical model of a U-tube evacuated tube solar collector. Four distinct velocities are used to examine the temperature distribution, convective heat transfer coefficient, useful energy gain, and fluid flow behaviour inside the collector's U tube. Higher temperature variations and heat transfer coefficient are observed with low inlet velocities. Maximum Reynolds, Prandtl numbers and useful energies are noticed with higher inlet velocities. It can be concluded that the U-tube configuration provides effective thermal absorption and fluid heating, making it suitable option for solar thermal applications. These numerical techniques serve as a foundation for further studies to optimize design parameters and incorporate advanced materials to enhance performance.

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