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Numerical Investigation of the Operating Parameters for Flat Plate Solar Collector: A Simulation-Based Study

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ABSTRACT

Due to a high reliance on fossil fuels, increasing depletion of indigenous fossil fuel supplies, a large burden on the national exchequer due to oil imports, and so on, Pakistan has been grappling with a severe energy challenge for decades. Solar energy has the potential to solve our energy problems. Despite the fact that Pakistan is located in the Sun Belt and receives over 2 MWh/m^2 of solar irradiation and 1500-3000 sunshine hours per year, we have not been successful in harnessing solar energy. Solar energy is routinely collected with flat-plate solar collectors. Solar thermal systems are becoming common place in both residential and business settings. The Novel Helical Flat Plate Solar Collector (FPSC) was numerically simulated in this work. Nano fluid and Pure water were used simultaneously in a Helical Dual Pipe as the thermic and operating fluid respectively. Ansys FLUENT, a commercial CFD package, was used to run the numerical simulations. The performance of FPSC was studied for Jamshoro district with hot climates, three velocity magnitudes (0.001,0.003 and 0.005 m/s) and five tilt angles (0°, 15°, 30°, 45° and 60°). Results concluded that the maximum exit water temperature in Jamshoro at a tilt angle of 0° was 382 K.

Keywords:

Computational Fluid Dynamics, Flat Plate Solar Collector, Tilt angle, Helical Duel Channel

1. Introduction

Since a few decades ago, Pakistan has been experiencing a severe energy crisis as a result of its excessive reliance on fossil fuels , rapid local fossil fuel reserve depletion, high load on the national budget from oil mainly furnace oil imports, etc.[1] Solar energy in particular and renewable energy in general have the ability to solve our energy issues. According to National Electric Power Regulatory Authority (NEPRA)" Pakistan is perfectly situated to benefit from solar energy technologies because it is located in the Sunny Belt. In Pakistan, the yearly average sun irradiation is about 5.5 kWh/m^2. Pakistan is located between latitudes 23.459 to 36.75c2N and longitudes 61Q to 75.5gE"[3].

Unfortunately, a number of constraints, including the initial high cost of solar panels, maintenance problems, import charges, a lack of supportive regulations, a lack of knowledge, and a lack of research and development (R&D) in this particular field have prevented us from fully utilizing solar energy. Solar energy benefits include offering off-grid options to the rural population who lacks access to electricity, reducing deforestation, increasing energy security because solar energy is locally accessible, sustainable and doesn't need to imported, providing green energy etc. Pakistan uses solar energy for a variety of purposes inducing photovoltaic and solar thermal ones like solar water heaters, cookers, dryers, and solar desalination.

Solar radiation is frequently collected with flat plate solar collectors. Solar thermal appliances are widely used in both household and commercial settings nowadays. A typical thermal solar collector can be utilized for both heating and the production of domestic hot water (DHW). In recent years, a number of a system configurations have been created to lower the energy consumption of heating systems and their operational expenses [4].

The Flat Plate Solar Collector (FPSC) has long been a practical and affordable option for capturing solar energy. Studies on the FPSC have been done in a variety of ways to try to understand how it operates. On the performance concerns with various regional coordinates and tilt angles around the world, including Iran, the United States, Germany, China etc., and numerous research have been done. The implications of regional coordinates and tilt angle performance of FPSC in - Pakistan are discussed in a few published research.

The principal concern for the designing of FPSC is that because of the absence of optical concentration / translucent Pipes such as iron pipes etc. The area from which heat is lost is very large because heat does not penetrate uniformly inside the pipe towards the fluid. Also, due the same reason higher temperatures cannot be attained. One of the possible solutions can be working with the Nanofluids that can save energy which can be released to running fluid (water). In order to verify the hypothesis, we would like to study the effect of different design and operating parameters at different coordinates of Pakistan. These effects will be examined using computational fluid dynamics (CFD).

2. Methodology

2.1. Development of CFD Model

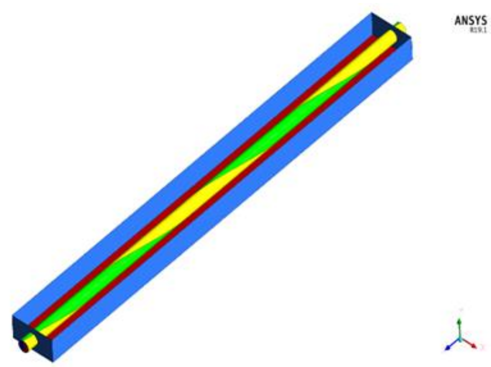
Three steps are involved in developing a CFD model: pre-processing, processing, and post-processing. During pre-processing, a meshed geometry of the chosen system is created using sophisticated software; this meshed geometry is referred to as the "computational domain." For this research study, the 3D geometry of the FPSC was created in ANSYS Design Modeler® as a pre-processing step. Afterwards, during the processing step, the relevant governing equations are typically solved with a commercial CFD code such as ANSYS FLUENT®[5]. In the current work, the relevant governing equations are listed in Table 1. The equations were solved iteratively until a converged solution was reached. After solving the equations repeatedly, a convergent solution was obtained.

Table 1: Few Pre-Selected Governing Equations for CFD Analysis

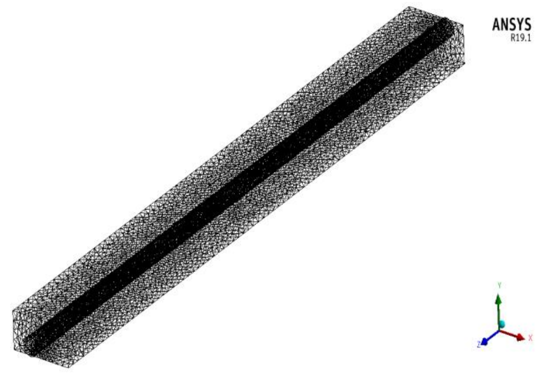
Physical Quantity	Equation	Eq. No.
Mass	$\nabla.(\rho \vec{v}) = S\_m$	(1)
Momentum	$\nabla.(\rho \vec{v} \vec{v}) = -\nabla p + \nabla.(\bar{\bar{\tau}}) + \rho + \vec{F}$	(2)
Energy	$\nabla.(\vec{v}(\rho E + p)) = \nabla.\left(\lambda_{eff}\nabla T - \sum_j h_j \vec{J}_j + (\bar{\bar{\tau}}_{eff}.\vec{v})\right) + S_h$	(3)
Standard *k-ε* Turbulence Model	$-\rho\overline{u_i' u_j'} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\rho k\delta_{ij}$	(4)
Radiation Model (P1)	$-\nabla q_r = aG - 4aG\sigma a^4$	(5)

2.2. Computational Domain

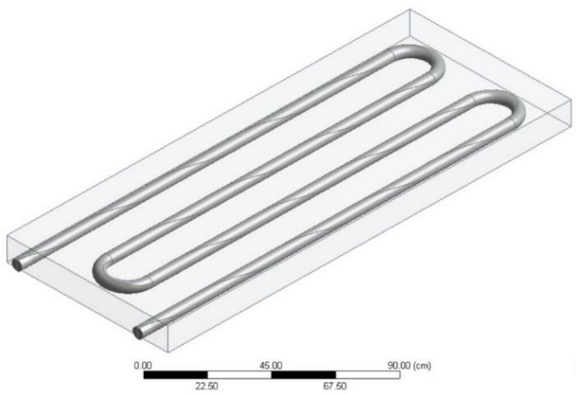
ANSYS DesignModler®16 was used to build the FPSC's geometry. Fig. 1 displays the created 3D geometries of the FPSC with round tubes together with its meshing computational domain. In order to simplify and minimize overall computing demands, the FPSC model is fitted with a single tube that has two passages, through which water circulates as the FPSC's working fluid. The fluid enters the geometry through the intake zone and leaves through the outlet zone. It was believed that the FPSC's top plate was composed of glass. The bottom copper plate of the FPSC was thought to be an absorbent plate. Using an uneven meshing approach, the mesh was created using tetrahedron cells. A total of 538113 cells with a minimum orthogonal quality of 0.251 were used in the generated computational domain. For computations, an orthogonal quality of more than 0.2 is typically regarded as good. After doing a grid independence test, it was discovered that this grid produced the best results. Similarly the single pipe numerical domain was extended to the full scale Flat Plate Solar Collector (Fig. 1).



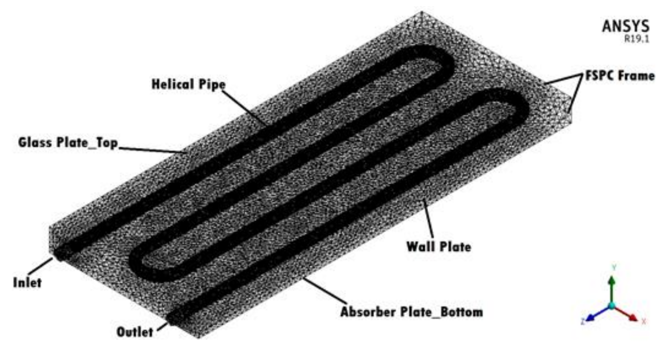
Single Helical Dual Channel pipe



Meshing of Single Helical Dual Channel pipe



Helical FPSC



Meshing of and Boundary Conditions

Fig. 1: 3D geometry of Helical FPSC, Meshing of Numerical Domain and Boundary Conditions

2.3. Assumptions and Convergence Criteria

As previously said, this paragraph differs greatly from the others in that it explains how the FPSC boundary conditions were applied to the computational domain utilized for the research project. First, it was believed that the fluid flow was completely developed and constant. Additionally, the numerical problem was made simpler by assuming that the fluid flow was incompressible under the boundary conditions and ignoring the radiation of heat losses. Additionally, the tube's axis was the direction of flow. Thermo physical, thermal conductivity, temperature, and fluid density were among the properties that were considered in the calculations. Table 2 lists the characteristics of the wall materials that were employed. Every surface of the wall was subject to the non-slip condition. Using the shell conduction technique, the heat conduction for the absorber and riser tube was calculated. To find the combinations, the SIMPLE method between the pressure and velocity was employed. These numbers, which were 00.95 and 00.91, respectively, were used for the absorber's transmissivity and absorber's absorptivity in the flat plate solar collector. Upon achieving the mass, turbulent kinetic energy, and momentum residuals fulfilled at 10^{-3}, as well as the energy residuals and radiation at 10^{-5}, the solution began to converge.

Table 2: Thermo-Physical Properties of Materials

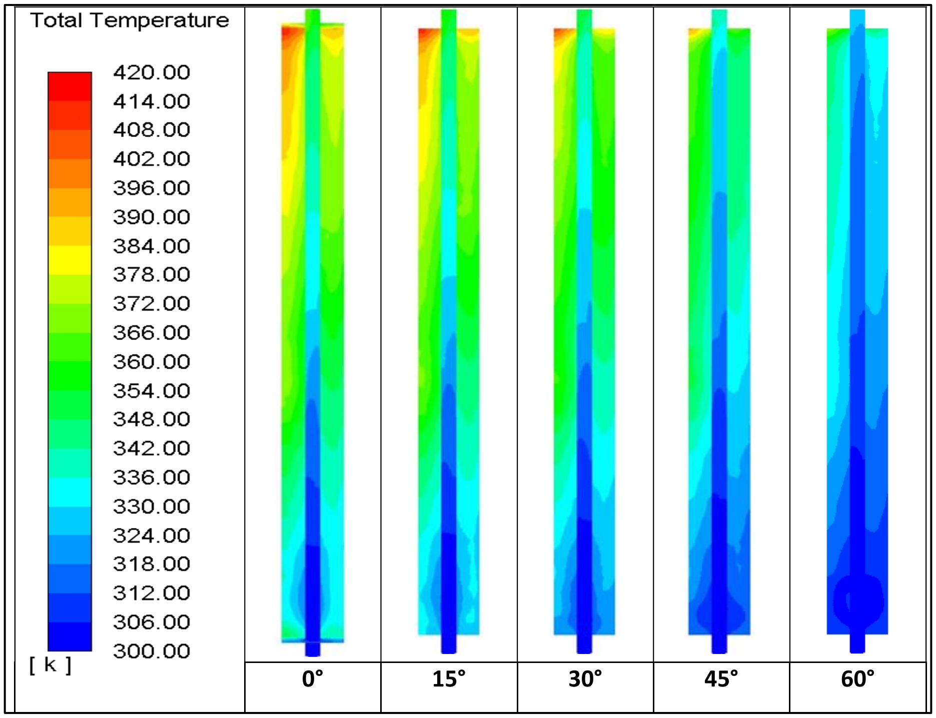
Sr. No.	**Material Used**	**Density (ρ)**	**Specific Heat (Cp)**	**Thermal Conductivity(K)**	**Viscosity (μ)**
		Kg/m^3	J/Kg-K	W/m-K	Kg/m-sec
1	Water (liquid)	998.2	4182	0.6	0.001003
2	Nano fluid	986	3805.9	40.54	0.001053
3	Copper (Solid)	8978	381	387.6	-
4	Glass	2489	754	1.75	-

3. Results and Discussions

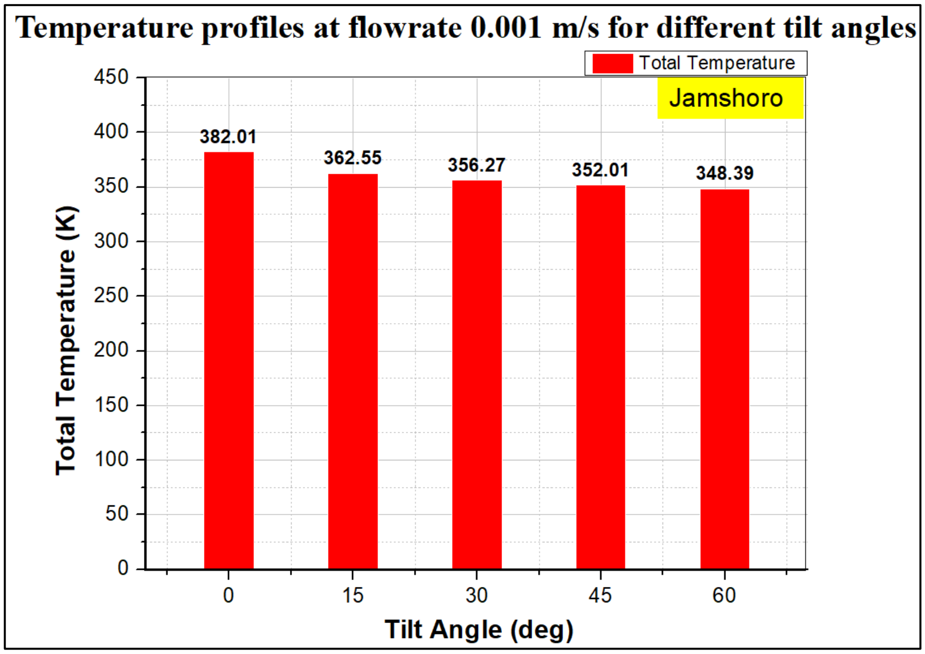
3.1. Performance of FPSC at different velocity magnitudes and tilt angle

The outcomes of those simulated scenarios, which were created by maintaining the flat plate solar collector at a 0° degree tilt angle for Jamshoro city. It indicates that the FPSC was positioned horizontally on the earth in those circumstances. Later, more cases were also replicated using just the Jamshoro location varied tilt angles (15°, 30°,45° and 60°) and flow rate velocities such as (0.001,0.003 and 0.005 m/s).

The temperature trend of the outflowing water from the FPSC at 0°, 15°, 30°,45° and 60° tilt angles, respectively, for the chosen city (Jamshoro), is depicted in Fig. 2 (a & b) with 0.001 m/s, Fig. 3 with 0.003 m/s, and Fig. 4 with 0.005 m/s respectively. The findings showed that the trend in outflow water temperature varies with tilt angle. By raising the tilt angles, this trend shows that at larger tilt angles, the outflow water temperature reduces (Figs. 2 a & b).



(a)



(b)

Fig. 2: (a) Temperature profiles at different tilt angles at flow velocity of 0.001 m/s and (b) average temperature

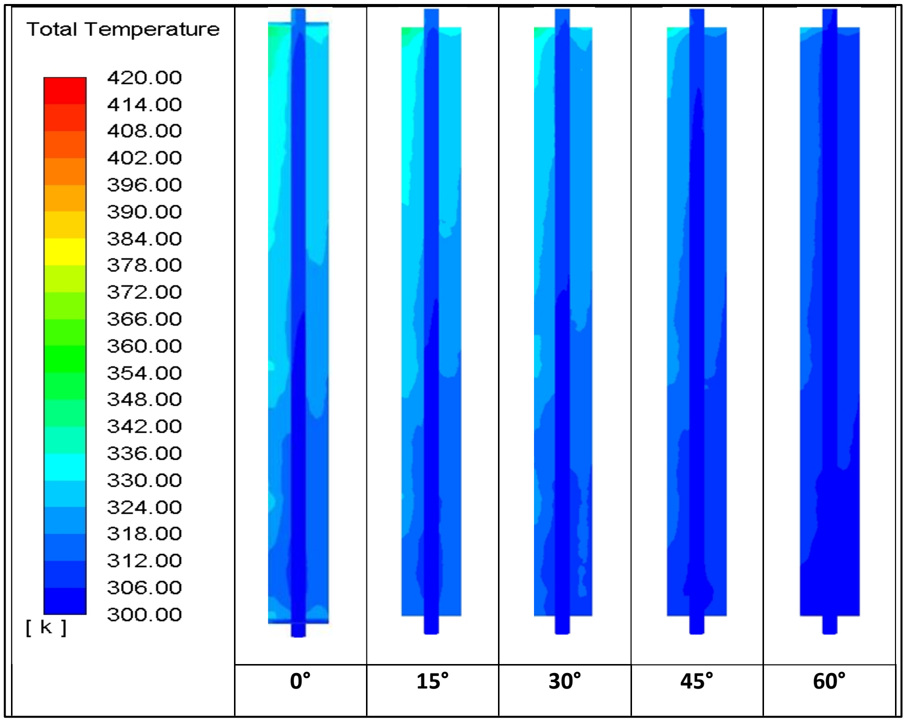


Fig. 3: Temperature profiles at different tilt angles at flow velocity of 0.003 m/s

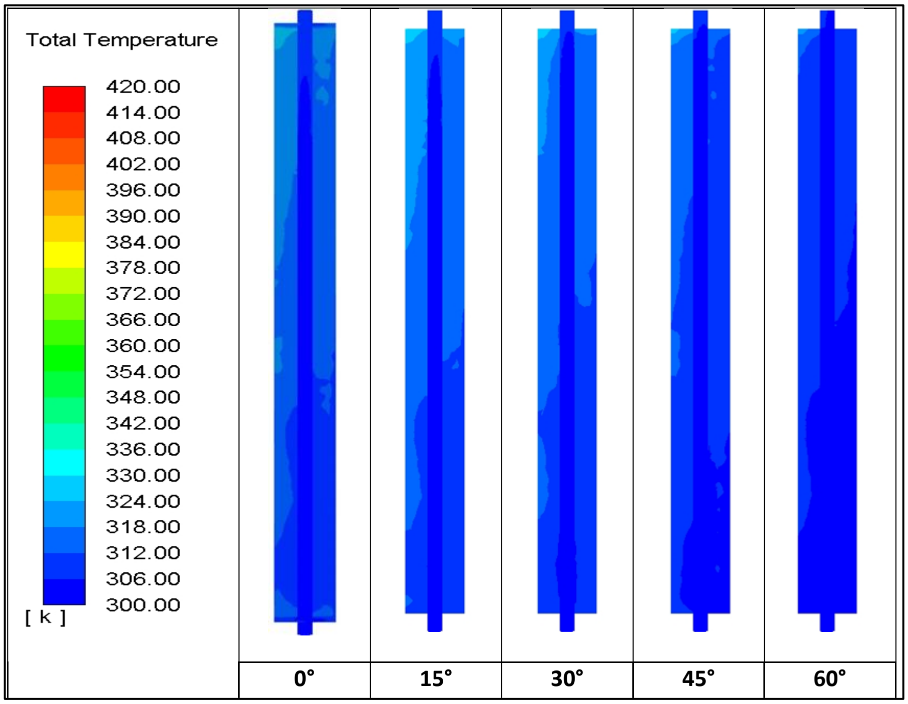


Fig. 4: Temperature profiles at different tilt angles at flow velocity of 0.005 m/s

3.2. Temperature Contours of FPSC Throughout The Year (Quarterly) For Selected Regional Coordinates

One method to qualitatively examine the developed model is to use temperature contours. One may see the various temperature levels in the object or area of interest as well as the temperature of the selected region displayed on a colored scale. The temperature contours for Jamshoro city throughout the quarter month are displayed in Fig. 5. These graphs show how different months affect the overall FPSC by showing how the red colour shifts from a limited region (during winter months like September and December) to a larger region (during summer months like March and June). These contours unequivocally demonstrate that the sun's shadow reaches its greatest in the summer because of the cities' geographic location. Another thing to note about the contours is that the colour of the entering water is depicted in blue. This indicates that cold water, at 300 K (27°C), is always entered in every scenario. Heat transfer from the hot environment which is mostly created by the absorbing plate occurs as the water gets warmer as it moves toward the outlet along the tube. It is at a greater temperature as it exits the tubes, and that temperature has already been recorded and thoroughly covered for each case. May through June are the hottest months because of the sun's nearly vertical position during those months, which increases the amount of heat transmission that occurs. The optimum velocity magnitude (0.001 m/s) and tilt angle 0^{o} at critical day and time (12:00) of June 21^{st} were simulated in the Novel Helical Dual Channel Flat Plate Solar Collector and are shown in Fig.6. which shows the highest achievable temperature at outlet was 382K.

4. Conclusion

The current study involved the numerical simulation of a Novel Flat Plate Solar Collector (FPSC). Water served as the operational fluid. Numerical calculations were performed using the commercial CFD code Ansys FLUENT. The FPSC model was initially set up with a 0° tilt angle, or parallel to the ground, and its performance was assessed for different flow rate velocities in terms of outflow water temperature. Afterwards, additional investigation was conducted to look into how well the FPSC performed at different tilt angles, such as 15°, 30°, 45° and 60°. The following are the closing thoughts:

- Regardless of location or season, it is determined that the FPSC raises the inserted water temperature from 27°C to greater values.
- At a 0° tilt angle, the performance of FPSC was at its peak from March to September.

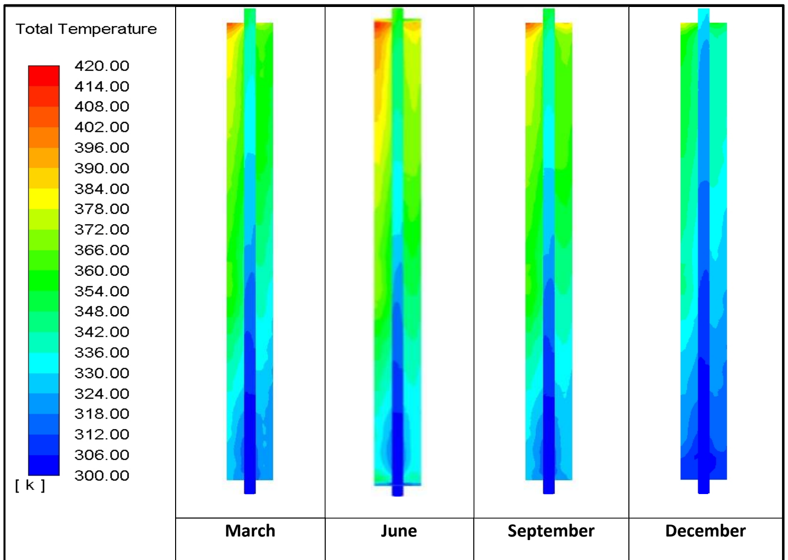
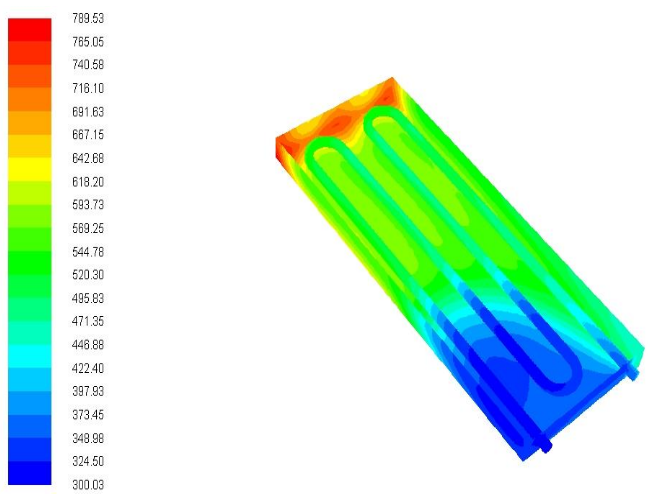


Fig. 5: Temperature contours at 0° tilt angle throughout the year

Fig. 5: Temperature profiles at 0º tilt angle throughout the year



Jamshoro_0º helical tray june_0.001 m/s

Inlet temperature(K): 300.00 Outlet temperature(K)= 382.46

Fig.6: Novel Helical Dual Channel Flat Plate Solar Collector

- The month of June saw the highest water temperatures from FPSC across the district, while December saw the lowest temperatures.Based on the data, the highest temperature recorded was 382 K in jamshoro city.

- It is also determined that the temperature at which water exits the FPSC varies greatly depending on the tilt angle. Because of the tilt angle, the temperature's highest and lowest values were likewise moved from warmer to cooler months.

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