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Numerical Simulations of Solar Curved Plate Collector for evaluating its performance

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ABSTRACT

Solar plate collectors are used to harness the solar energy in the form of heat the fluid like water. They are simple in operation and easy to fabricate. Currently various designs of solar plate collectors are available like solar flat plate collector (SFPC), Solar Parabolic Collectors, and Solar Curved Plate Collectors (SCPC). SCPC is comparatively a new design and researchers are investigating its performance in various perspectives. In present research, a 3D CFD model of SCPC has developed to investigate its performance in local regions of Pakistan. Ansys FLUENT was used to simulate the SCPC. Steady state equations of mass, energy and momentum were solved numerically. Solar ray tracing model was used to incorporate the solar radiation effect with respect to selected global coordinates. Three cities of Sindh Province i.e. Hyderabad, Dadu and Sukkur were selected. The inlet flowrate and temperature of fluids were kept at constant values of 0.0025 kg/sec and 300 K (27°C) respectively. The computations were performed for all months (January to December) by taking water as working fluid. Air was also used to investigate the effects of different fluids on the performance of SCPC in selected regional coordinates. From the results, it was observed that SCPC has shown good performance in the month of July with Air fluid. The average maximum Temperature with water as working fluid was observed from all the locations in the range of 345 K (72°C) in the months of July. The maximum Air temperature i.e. 491 K (218° C) was achieved in the month of June at Hyderabad.

Keywords:

Solar Curved Plate Collector (SCPC),
Solar Ray Tracing Model
CFD

1. Introduction

From the past few decades, Pakistan is facing serious energy crisis, owing to heavy dependence on fossil fuels, depletion of local fossil fuel reserves at a faster pace, heavy burden on the national exchequer, due to import of oil, etc. Renewable energy, in general, and solar energy, in particular, has the potential to mitigate our energy problems. Although, Pakistan lies in the Sun-Belt and receives plentiful solar irradiation of over 2 MWh/m2 and 1500-3000 sunshine hours every year, unfortunately, we have not been very successful to harness solar energy to its full potential, due to different factors, such as, initial high cost associated with solar panels, maintenance issues, import duties, lack of supportive policies, lack of awareness and lack of R&D, in this specific area. Solar energy has the advantages of providing off-grid solutions to the un-electrified rural population, decreasing deforestation, energy security as solar energy is locally available, sustainable and need not to be imported, providing green energy, etc. The various applications of solar energy in Pakistan, include; photovoltaic and solar thermal application, such as, solar water heaters, solar cooker, solar dryers and solar desalination [1].

Improving performance of sustainable energy systems is getting much more attention these days according to the environmental issues related with fossil fuel energy consumption. One of the most common and well established technologies of harvesting solar energy is the plate collector for hot water production [2]. There are various types of domestic solar water heaters including the flat plate and curved collectors. Flat plate collectors can be designed for applications requiring energy delivery at moderate temperatures and are usually cheaper that other types [3]. They use both beam and diffuse solar radiation, do not track the sun and require little maintenance

Flat-plate solar collectors are widely employed for collecting solar radiation. Nowadays, solar thermal systems have reached a large diffusion as domestic and commercial appliances. A standard thermal solar collector can be used both for domestic hot water (DHW) production and for heating purpose. Several system configurations have been developed in the last years to reduce the energy consumption of heating systems and their operating costs [4].

The conventional flat plate solar air heater (SAH) has been widely used worldwide for solar thermal conversion. A key factor to evaluate the performance of SAH is its thermal efficiency. Various research works has been going on in order to enhance its performance. The transformation of smooth flat rectangular flow channel into curved one. The Curved panel show significant increase in the outlet air temperature and, hence thermal efficiency when compared with flat plate SAH [5].

Tilt angle and orientation influence the amount of solar radiation reaching the collector; this is due to the changing incidence angle. Using a sun tracking system is one way to maximize the solar radiation[6, 7], but tracking is not always applicable as a result of the expenses of purchasing the system; additionally, such a system needs electrical energy for operation. Determining optimum tilt and orientation angles in a specific period of time and adjusting the collector accordingly are the alternative ways. The optimum tilt angle should be determined in order to maximize the solar radiation on the collector in a specific period of time [8].

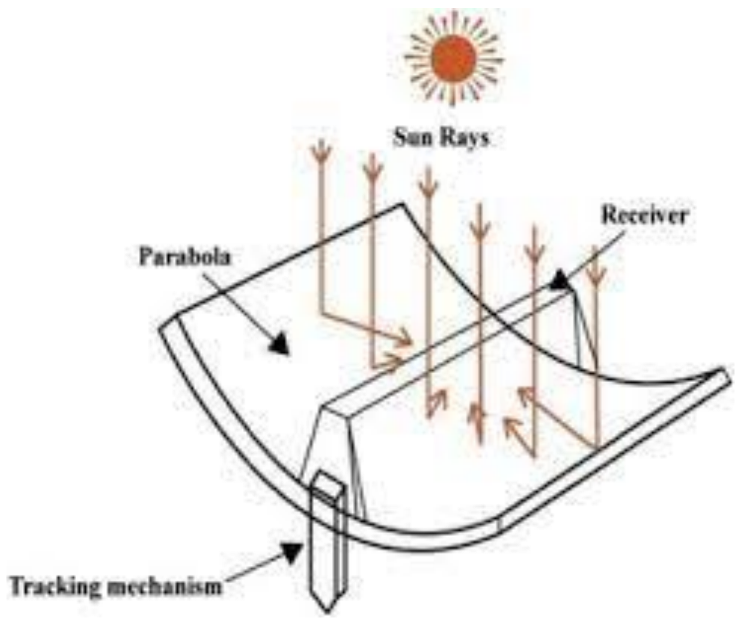


Fig. 01: Curved Plate Collector

Studies have already been done in several places with different climatic conditions. Generally, the results are reported as a function of site latitude for a specific period of time. Siwen and Himsar 2020 discussed the performance of 2 types of pipes. The first straight pipe type and the second pipe type U Curved Pipes. With CFD simulation methods and variations in fluid flow velocity, the results of changes in fluid temperature of the fluid came different from the 2 types of pipes. The increase in temperature was observed in liquid air in the pipe faces 0.9425% compared to straight pipes [9]. Singh and Singh (2018) investigated various curved solar air heater designs that showed significant enhancement of heat transfer. The Computational Fluid Dynamic (CFD) model was first validated by published results. It was observed that secondary vortex formation near the absorber wall increases the Nusselt number significantly [5]. Ghasemi and Ranjbar (2016) numerically simulated forced convection heat transfer turbulent fluid flow inside the receiver tube of solar parabolic trough collector. The CuO-water and Al_2O_3-water nanofluids were used in this study as working fluid. The Computational Fluid Dynamics (CFD) commercial code was employed to find hydrodynamic and heat transfer coefficients by means of Finite Volume Method (FVM) [10]. Mahboub et al., (2015) was aimed to find simple and tolerable solution to get rid of the inconvenience resulting from the widely adopted heat-transfer-enhancement techniques by providing an optimized solar air heater design. The proposed design consisted of a slightly curved smooth flow channel with an absorber plate of convex shape. A prototype of a curved solar air heater of 1.28 m2 collector area was built and tested under summer outdoor conditions in Biskra (Algeria) [11].

Unar et al., (2020) developed a three-dimensional computational fluid dynamic (3D-CFD) model of solar flat plate collector (SFPC) in order to investigate the effect of operating and geometric parameters on thermal efficiency. In this research work, commercial CFD code ANSYS FLUENT®14.0 version was used for the development of a model of solar plate collector. The single circular tube geometry was created using ANSYS DesignModeler®14.0. The general continuity equation along with Navied–Stokes equations was solved for tracking motion of the working fluid. The general k–ε turbulence modeling approach was used for solving the turbulence in the flow. Solar ray tracing was activated for calculating solar load in the model. The latitude and longitude of the Hyderabad region were inserted in the solar ray-tracing model for calculating solar intensity as per local conditions. Two fluids i.e., water and air were circulated with different flow rates in the developed model of SFPC. It was observed that water gave higher efficiency due to high density and thermal conductivity.

The optimum tilt angle for a solar collector was investigated in Syria. Daily, monthly, seasonal, and yearly optimum tilt angles were determined for cities by employing extraterrestrial radiation on the inclined surface. The optimum tilt angles of cities located at the same latitude angle are equal [12]. The optimum tilt angles were proposed for Izmir, Turkey. A mathematical model was used for determining monthly, seasonal, and yearly optimum tilt angles by employing a monthly clearness index. Yearly optimum tilt angle for Izmir was calculated to β_{opt} = 30.3° located at a latitude of φ 38° [13]. In the model developed for Amman, Jordan, the optimum tilt angle was determined in a general form; however, solar radiation was estimated by employing the clearness index. The yearly optimum tilt angle proposed β_{opt} =31.3°, and it was in good agreement with the one calculated by NASA (β_{opt} =28.8°) [14]. The optimum tilt angles for winter months, summer months, and the entire year were calculated in China, and a contour map of the optimum tilt angle was presented. The yearly optimum tilt angle was proposed as $\beta_{opt} = \varphi + (4 \text{ to } - 10)$ for different places [15]. The benefits of solar radiation on the inclined surface were determined for the solar tracker system and the optimum tilt angle in the United States which was more than 25% versus the yearly optimum tilt angle. The contour map of a yearly optimum tilt angle was shown, and the optimum tilt angle ranged from φ to (φ-10) [7].

In order to analyze the flow distribution inside a solar collector with horizontal inner tubes, Fan et al. [16] compared the experimental data obtained by several outdoor tests, with the CFD calculations performed using Fluent 6.1®. The collector is modeled assuming a uniform energy generation in the absorber tube and considering only a convective heat loss coefficient, calculated using external software SolEff® and set as an input for the CFD calculations. Selmi et al. [17] simulated a flat-plate solar collector in 3D geometry using the commercial CFD software CFD-ACE+® [18] the numerical results are compared with experimental data, showing good agreement in the temperature profiles. An experimental and numerical analysis was conducted by Turgut and Onur [19] to determine the average heat transfer coefficients for forced convection air flow over a flat plate solar collector surface. The Authors started from the work made by Sartori [20], who demonstrated that the most commonly used equation for the calculation of heat transfer coefficient [21-23], depending only on wind velocity, is in contrast with the boundary layer theory and does not correctly represent the convective heat transfer over the plate. Karanth et al. [24] adopted the Discrete Transfer Radiation Model (DTRM) inbuilt in Fluent 6.3®, to model the radiation heat transfer and the solar radiation. An extension of this work was made by Manjunath et al. [25], in which the same approach has been applied to an unglazed solar flat plate collector and by Manjunath et al. [26] in which different surface geometries of the absorber plate were investigated

Solar Plate Collectors (SPC) are always remained an economic and easy choice for harnessing the solar energy. SPC usually comes in two basic configurations, one is Solar Flat Plate Collector (SFPC) and other which is more recently developed i.e, Solar Curved Plate Collector (SCPC). SFPC is extensively studied in different direction regarding the understanding of its working mechanism. Several studies have conducted on the performance issues with different regional coordinates and tilt angle in the world like Iran, USA, Germany, China etc. SCPC is new concept with added benefits over SFPC like more heat absorption due to its curved nature.

Scant literature has reported regarding SCPC performance and working mechanism. Moreover, no study is conducted to check the performance of SCPC in the regional coordinates of Pakistan. Hence this research primarily focused on the investigation of performance evaluation with respect to different regional coordinates and different working fluids of SCPC. The computational fluid dynamics will be used to investigate these effects.

2. Model development

There are three steps in the development of CFD model. These steps are known as Pre-processing, processing and post-processing. In pre-processing, a meshed geometry of the selected system is developed using some advanced software. That meshed geometry is technically called "computational domain". All the steps are discussed in subsequent paragraphs.

2.1. Development of SCPC Geometry

The geometry of the SCPC was developed in the ANSYS DesignModler®19. The developed 3D geometries of SCPC with circular tubes are shown in Fig. 2 along with its meshed computational domain. The fluid is inserted from inlet zone of geometry, and it exits from outlet zone. The upper plate of SCPC was considered as made up of glass. The bottom plate of the SCPC was considered as absorbing plate made up of copper. The mesh was developed with tetrahedron cells using uneven meshing strategy. Total number of cells used in the developed computational domain were 654324 with minimum orthogonal quality was 0.483.

2.2. Governing Equations

In present work the concerned governing equations which have solved are given in Table 01. The equations were solved iteratively and a converged solution has achieved [22].

The radiative transfer equation (RTE) was quite convenient and efficient in participating media for describing the radiations phenomena due to the sum of the given contributions of all the rays crossing into the cell.

The number of rays and their directions, and that was selected by RTE [12], was solved on its way for each ray from boundaries to boundaries. And the general basis for this given method was to quantify coefficient of the absorption and the given temperature with constant within a volume of single control were assumed.

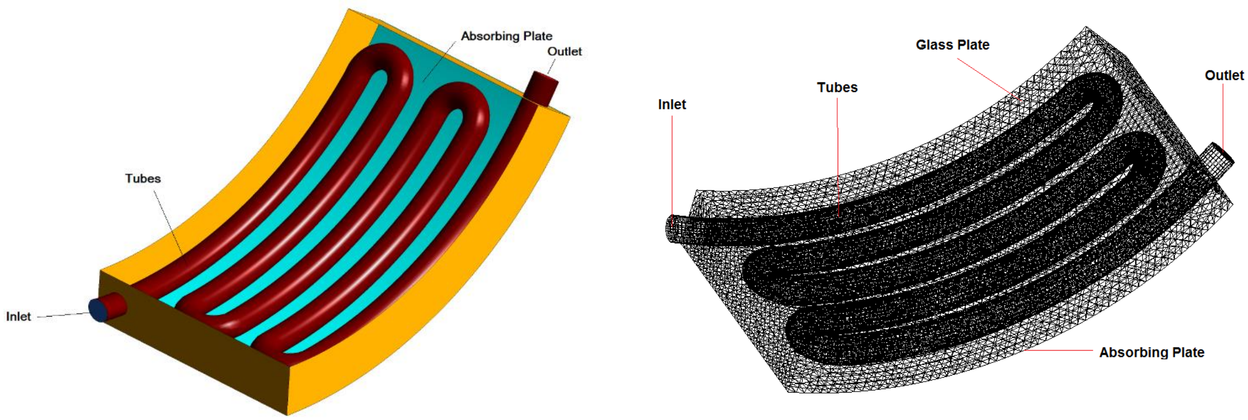


Fig. 02: 3D geometry of SCPC and its mesh

Table 01: Governing Equations of the selected system

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)
The Intensities of heat radiation	$i'_{n+1} = i'_n(1-\varepsilon(T,x_i)) + i'_b(T)\varepsilon(T,x_i)$	(6)

2.3. Assumptions and Convergence Criteria

The flow of the fluid was assumed fully developed and to be steady state flow. The numerical problem was simplified by neglecting the radiation heat losses in these circumstances and the flow of the fluid was assumed to be incompressible in the boundary conditions. The properties of wall materials used are tabulated in Table 02. Non-slip condition was applied at all wall surfaces. The absorptivity of the absorber and transmissivity of the glass of the solar flat plate collector were 00.95 and 00.91, respectively. The solution was converged when the mass, turbulent kinetic energy and momentum residuals satisfied at 10^{-3} and energy residuals and radiation at 10^{-5} was achieved.

Table. 02: Thermo-physical properties of materials

Material Used	Density (ρ)	Specific Heat (Cp)	Thermal Conductivity (K)	Viscosity (μ)
	Kg/m^3	J/Kg-K	W/m-K	Kg/m-sec
Water (liquid)	998.2	4182	0.6	0.001003
Air	1.255	1006.43	0.0242	1.789×10^5
Copper (Solid)	8978	381	387.6	-
Glass	2489	754	1.75	-
Wood	700	2310	0.173	-

2.4. Boundary Conditions and Operating Parameters

For investigating the performance of SCPC at different regions of Pakistan, three cities of Sindh province were selected i.e., Hyderabad (HYD), Dadu (DAD) and Sukkur (SKR). The analyses were conducted throughout the year in each month at 12:00 PM daytime. To investigate the effects of different fluids, the simulations were also conducted with air fluid in Hyderabad city. The inlet flowrate and temperature of fluids were kept at constant values of 0.0025 kg/sec and 300 K respectively.

3. Results and discussion

The results in the shape of outlet temperature and temperature profiles were extracted from the converged solutions of all the cases. The results are discussed in following paragraphs.

3.1. Comparison of Results with Literature

The SCPC have also utilized by Pirzada et al., (2021) [27] to investigate the performance of SCPC in the cities of China. The similar geometry has developed in current research hence the results are compared in presented in Fig. 03.

From the Fig. 03, it has observed that the average temperature of exiting fluid from SCPC is about 72°C which is bit similar from most of Chinese cities as per Pirzdada et al., (2020) [27]. Hence the model configuration along with solution of selected differential equations are considered acceptable with insignificant numerical errors. However the exact validation of the computational results could be made without the exact experimental conditions along with actual system with exact dimensions.

3.2. Effects of Months on Performance of SCPC at selected cities

Three locations i.e., Hyderabad, Dadu, and Sukkur, were selected to investigate the performance of SCPC in terms of increased temperature of exiting fluid.

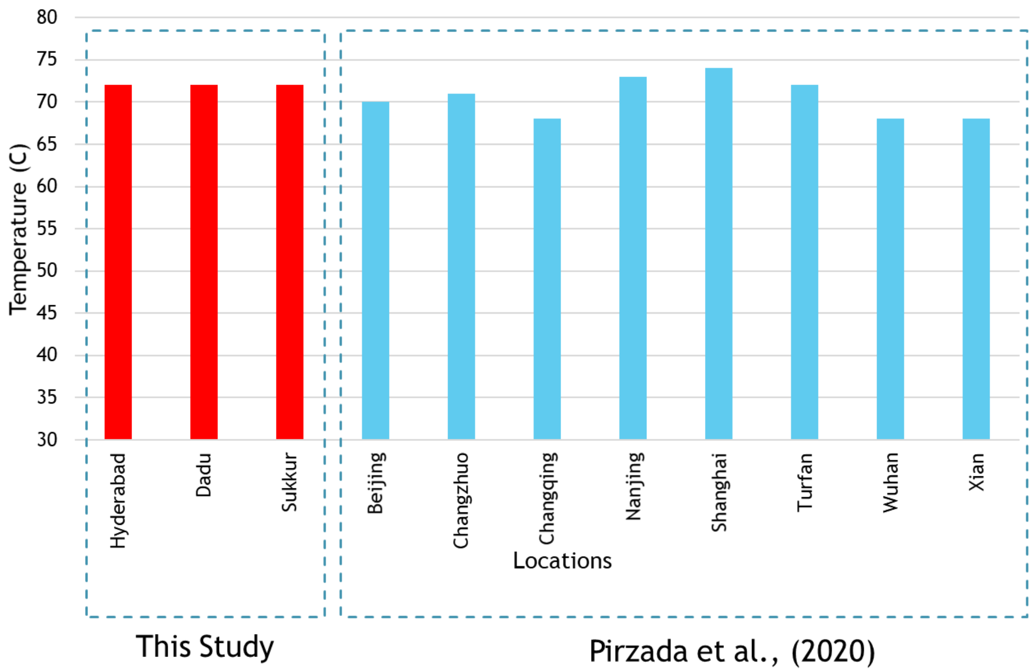


Fig. 03: Comparison of simulation results with literature data on similar geometry of SCPC

The working fluid was water and keeping the constant inlet flowrate and inlet temperature, the analysis was made. Fig. 04 shows the exit temperature of fluid which was calculated for all the cities from January to December. From the figure, it has seen that in the winter months (November, December, January, and February), the exit temperature of water got increased much lower as compared to summer season (March to October). The reason is obvious that in summer the location of sun over Pakistan is closer to perpendicular which in turns has direct solar radiation and has greater effect on the fluid temperature rise. Moreover, it was also observed that in any month the temperature of exiting fluid was higher for Hyderabad city as compared to other two cities. The highest temperature of exit fluid was observed 345.5 K (72.5°C) in the month of July for Hyderabad and Dadu cities whereas the minimum temperature was observed 326.6 K (53.6°C) in the month of December at Sukkur city.

3.3. Effect of Working Fluid at Same Location

In current research, initial simulations were made with water as working fluid. Later, to investigate the effect of working fluid, Air was also used as working fluid and in first group of simulations, the location was kept constant at Hyderabad. Fig. 05 shows the comparative results in terms of temperature of exiting fluid for all the months with both working fluid in Hyderabad city.

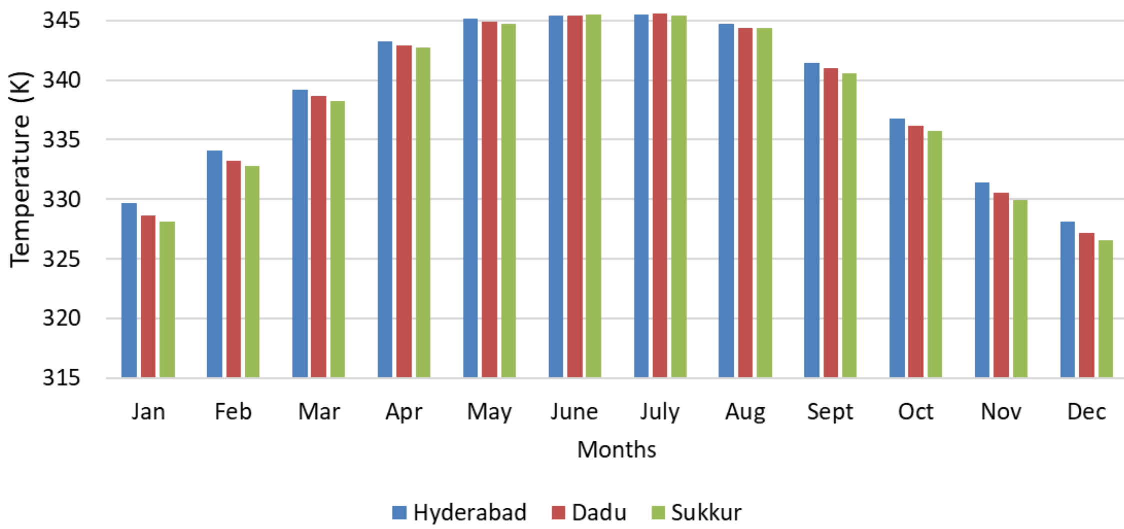


Fig. 04: Monthly effect on performance of SCPC at selected locations

The air fluid gave a higher temperature in each month as compared to water. The reason is the higher values of specific heats of air. Once air is heated then it remained heated for whole the time. The maximum temperature with Air fluid was recorded 491 K (218 °C) in the month of June whereas the minimum temperature was estimated 417 K (144°C) in the month of December.

3.4. Effects of Working Fluid with different locations

After investigating the effects of working fluids on the performance of SCPC throughout the year at same location (Hyderabad), the performance of SCPC was also evaluated with both the working fluids at all selected cities only for the month of June. Fig. 06 shows the trend observed at all three locations. No significant difference was observed in the temperatures for both the working fluids. Almost all the locations have shown similar temperature with water i.e., 345.5 K (72.5°C) and 491 K (218 °C) for air.

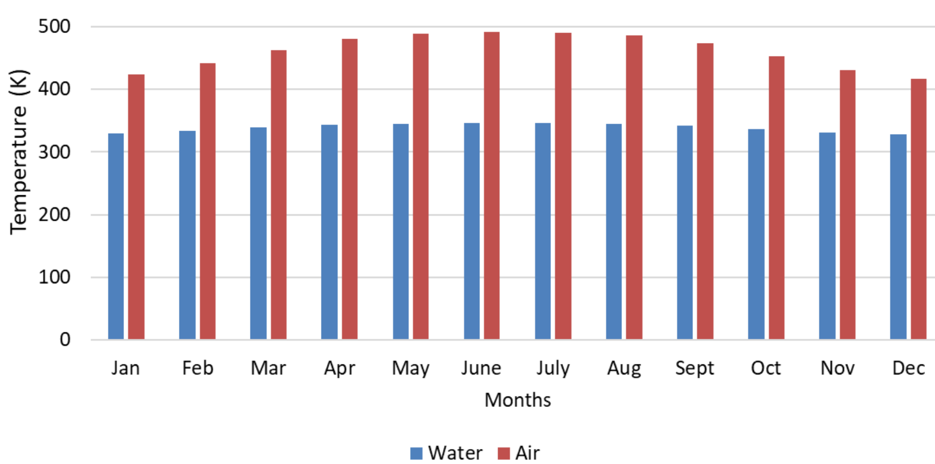
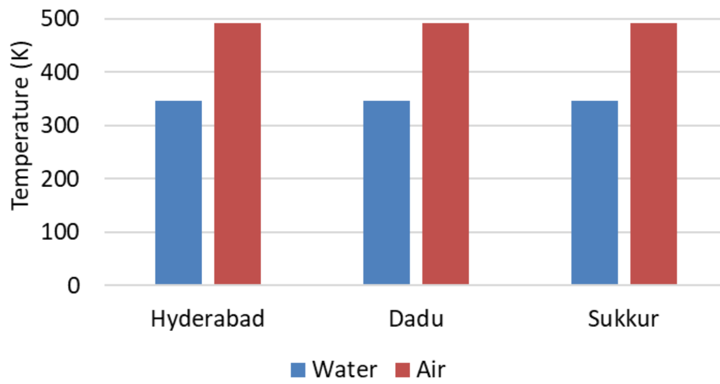


Fig. 05: The effects of working fluid on the performance of SCPC at Hyderabad City



4. Conclusion

It is concluded that different cities of Sindh province of Pakistan has no major impact on the overall performance of SCPC in the summer season (May to July). However little higher exit fluid temperatures were observed for winter at Hyderabad than Dadu and Sukkur. The average maximum Temperature was observed from all the locations in the range of 345 K (72°C) in the months of July. The maximum temperature was achieved at 12:00 PM in the month of JUNE so this time is considered best for SCPC performance. Air fluid has shown higher temperature rise as compared to water due to low thermal conductivity. The maximum Air temperature i.e. 491 K (218° C) was achieved in the month of June at Hyderabad.

The work may be extended by to conduct the analysis for other locations of Pakistan. The transient simulations would also be conducted to see the transient heat transfer during the day. The experimental investigations could also be performed.

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