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Thermal and Hydraulic Performance of Flat-Plate Solar Collector for Different Riser Configurations

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Abstract

The demand for energy is ever increasing. With the depletion of non-renewable energy resources, a gradual shift towards the utilization of renewable is required. Hence, in the present work, we have studied flat-plate solar collector, for harnessing solar energy, for application like domestic usage, pool heating and inductrial applications. Different riser configuartions is viewed as a part of the current research, and the thermohydraulic performance is compared computationally.

Keywords:

Solar energy;
Solar irradiation;
Thermal Performance;
Hydraulic performance;
Flat plate Solar collectors.

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1. Introduction

Electricity has been the most widely used form of energy. It is used in lighting, cooling and refrigeration, industries and in appliances like computers, electronics, machinery, and public transportation systems. A huge amount of coal is processed at thermal power plants to generate electric power, inorder to fulfil the demand of electricity. Coal is an important non-renewable source of energy but it has also limited deposits. Solving the mentioned problem, flat-plate solar systems are utilized for encapsulating thermal radiations emitted by sun. The radiation increases the temperature of water flowing through the riser tubes fitted between glazing and absorber plate in the collector system. The hot water thus obtained at the outlet is used directly or it is used for auxillary heating purposes.

Key applications of solar collector include domestic water heating, pool heating, and other industrial applications. Solar heating has also emerged as an advantageous technique for desalination of water [1]. A wide group of researchers have studied analytical [2] numerical [3] computational and experimental model [4] of solar collector for its optimization, further

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enhancing its thermal performance. Baccoli *et al.* [5] studied the mathematical model of the solar collector which uniquely captured the anisotropic behaviour of sky. Further, Ziqian Chen *et al.* [6] characterized the collector system by means of critical coefficients, such as the film (convection) transfer coefficient, plate absorbtivity or emissivity, via nonlinear optimization techniques, applied to steady state conditions. Dawit Gudeta Gunjo *et al.* [7] and Mohamed Selmi [8] studied the solar collector system using CFD package. Mohsen Sheikholeslami [9] presented a review on heat transfer enhancement method, focusing on passive method using swirl flow devices. Swirl flow devices, like twisted tape, have been a key element for improving the thermal characteristics of the solar collector. Swirl was generated by evenly spaced twisted-tape elements which vary in twist ratio and rotation angle [10]. In addition, the thermo-hydraulic performance of twisted tape insert depends on the flow conditions, i.e., laminar or turbulent flow apart from the insert configuration [11]. Later, a new dynamic test method was introduced by Weiqiang Kong *et al.*[12] so called improved transfer function method features on two new collector parameters were introduced. One parameter is time term, which can indicate solar collector's inner heat transfer ability and the other is a second order term of collector mean fluid temperature, which can obtain fluid thermal capacitance.

Balaram Kundu [13] presented an analytical analysis of both Fourier and non-Fourier heat conduction in the absorber plates of a flat-plate solar collector. Later, Molero Villar *et al.* [14] developed a transient 3-D mathematical model for solar flat plate collectors. Moreover, Dongwei Zhang [15] presented a physical model of two-phase closed thermosyphon is established by taking account of the thermal resistance networks. A wide range of heat transfer enhancers were developed, which are frictionally engaged with the inner surface of the wall, kept in axial direction, along the fluid flow path [16] Moreover, the applied passive methods based on the enhancement of shear-produced turbulence are ineffective in augmenting heat transfer to the collector fluid in flat-plate solar collectors [17] due to significant damping caused by buoyancy forces. However, for general engineering purposes, the performance curves may be used for efficient and optimum design of liquid flat-plate solar collectors [18].

There are critical issues hindering the widespread use of solar energy. The first law of thermodynamics is not solely capable of demonstrating quantitative and qualitative performance of such systems [19]. When the instantaneous solar irradiance modulates sharply at one moment, most of the existing models cannot accurately predict the momentary thermal characteristics of outlet temperature of the working fluid and useful heat gain [20]. It was reported that the detailed analysis of a solar collector is a complex task, due to the large number of parameters affecting its performance [21]. The serious challenge is the availability of solar energy during summer. At a given time, the amount of the available solar energy depends on the weather conditions, location and the time of year. Solar energy received at a given location may vary considerably within an hour or even minutes. During winter season demand for thermal energy is high yet relatively lower amount of solar radiation can be received from sun. Motivated by the involved challenges, the present work focuses on the efficiency under various operating conditions.

2. Research Methodology

The present work has been performed computationally to predict the outlet temperature of water from riser tube. A computational method is used for the simulation because it gives the maximum favourable outcome of an experiment by excluding the possible losses.

Governing equations

The thermal radiation emitted by the sun falls on the solar collector place on the earth's surface. The radiant heat first transfers convectively from the atmosphere to the riser tube. The governing thermal equilibrium formulation for convective heat transfer from the atmosphere to the upper surface is

$$q_{x,1}=h_1A_u\left(T_{\infty,1}-T_1\right) \quad (1)$$

where $q_{x,1}$ is the convective heat transfer from the ambient to upper surface of riser tube, h_1 being the convective heat transfer coefficient and A_u being upper surface area of the riser tube and $T_{\infty,1}$ and T_1 are the ambient temperature and upper surface temperature of the riser tube.

The radiant heat reaching on to the riser tubes is taken in terms of heat flux. Considering steady-state one-direction heat transfer, thegoverning thermal equibrilium formulation for conductive heat transfer from the upper surface of riser tubes to the lower surface is

$$q_{x,2}=\frac{2\pi Lk_r\left(T_1-T_2\right)}{\ln\left(r_o/r_i\right)} \quad (2)$$

where $q_{x,2}$ is conductive heat transfer per unit area, L being the vertical length of riser tube, k_r(W/m-K) is the thermal conductivity of riser tube, T_1 and T_2 are outer and inner surface temperature of riser tube respectively. Similarly, r_o, r_i being the outer and inner radius of riser tube.

The heat flux at inner surface of the riser tube encounters the water flowing through tubes which leads to the convective heat transfer from inner surface of the riser tube to the water due to which the temperature of the water flowing through riser tube increases. Neglecting the thermal resistance at the interface between the inner surface of riser tubes and the outer layer of water the governing thermal equibrilium formulation is

$$q_{x,3}=h_2A_i(T_2-T_{\infty,2}) \quad (3)$$

Where $q_{x,3}$ is convective heat transfer rate, h_2 is convective heat transfer coefficient (W/m^2-K) and A_i is the inner surface area of riser tube. Similarly, T_2 and T_w are the inner surface temperature and temperature of water flowing the riser tube respectively.

At steady-state conductive heat traanfer between riser inner and outer surface is equal to the rate of convective heat transfer. Therefore, from equation (1) and equation (2) the following result can be derived.

$$q_x=h_1A_u\left(T_{\infty,1}-T_1\right)=\frac{2\pi Lk_r\left(T_1-T_2\right)}{\ln\left(r_o/r_i\right)}=h_2A_i(T_2-T_{\infty,2}) \quad (4)$$

An electrical-analogy has been developed in bid to incorporate all equations in a single equation. The equation for thermal resistance is

$$R=\frac{1}{h_1A_u}+\frac{\ln\left(r_o-r_i\right)}{2\pi Lk_r}+\frac{1}{h_2A_i} \quad (5)$$

Therefore, the total heat transfer from the upper surface of the riser tube to the water is

$$q_x=\frac{T_{\infty,1}-T_{\infty,2}}{R} \quad (6)$$

Riser configurations

The geometric configuration of the model has been discussed in this section. The diametre of the riser have been kept same for all three riser configurations. Table 1 shows the dimensions for riser tubes in each configurations.

Table 1. Dimension specification of riser tubes

Description	Specification
Diameter of riser tube (m)	0.017
length of inlet portion (m)	0.3
Length of Outlet portion (m)	0.3
Vertical length of riser tube (m)	0.67
Fillet radius (m)	0.02
Centre to centre distance between riser tubes (m)	0.055

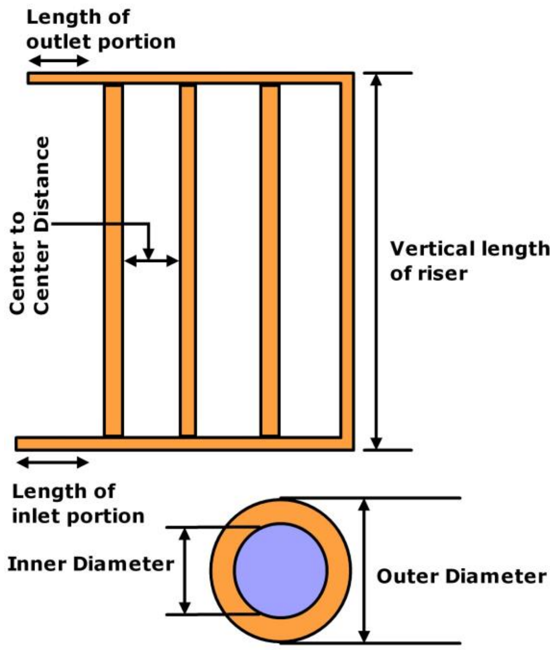

Figure 1 Dimension specification for riser configuration

Figure 1 represents the schematic representation of riser tube network in the flat-plate solar collector. The simulation have been performed computionally by using the CFD package. The models for three riser tube configurationare is prepared on the commercial code ANSYS. The following figure shows the computational model of the three types of riser configuration.

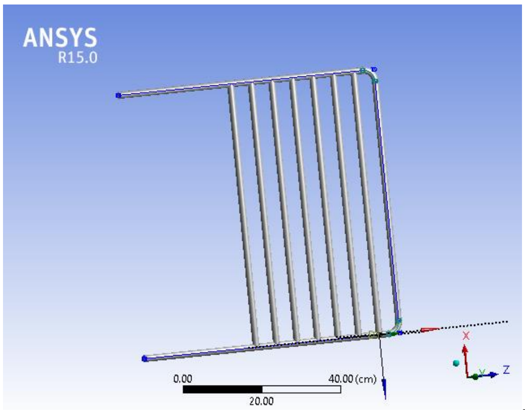

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Figure 2. riser configuration having inlet and outlet portions on the same side of the collector.

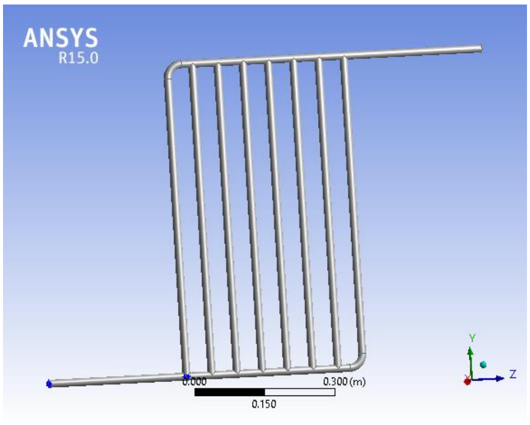

Figure 3. Riser configuration having inlet and outlet portions on the opposite of the collector

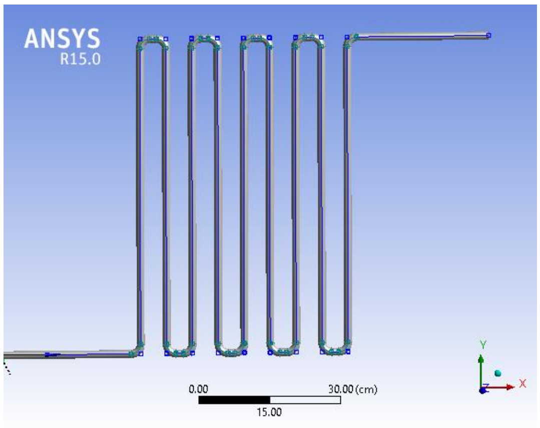

Figure 4. riser configuration with single riser tube with inlet and outlet portions of the opposite sides of collector

The riser configuration shown in Figure 2 have inlet and outlet portions of the same portion of riser tube. The riser tube configuration shown in Figure 3 have inlet and outlet portions of the opposite portion of collector. The upper and lower vertical tubes are known as header pipes. The third configuration of riser tube shown in Figure 4 has a single riser tube with no header tube. It is bent alternatively in order to increase the time span of water in the riser tubes. The dimensions specification for the riser configuration is same as shown in table 1. It is fine meshed in the mesh module and appropriate boundary conditions is imposed on it. The boundary condition applied on the riser configuration is same of all three riser configurations and they are shown in the table 2.

Table 2. Boundary conditions imposed on the riser configurations

Mass flow rate of water (kg/s)	0.01
Heat flux (W/m^2)	1000
Inlet water temperature (K)	300
Operating pressure (Pa)	101325

3. Results and Analyses

After preparing the model in the software, it was meshed in the module and the resultant mesh is shown in figure 4.

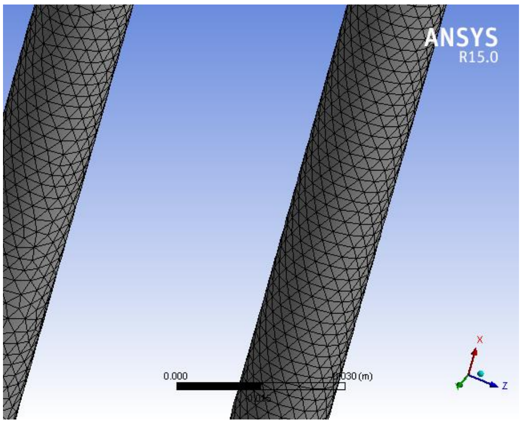

Figure 5. Mesh for each configuration of riser tubes

After applying the boundary conditions, the total temperature obtained shown in Figure 2 is shown in figure 4.

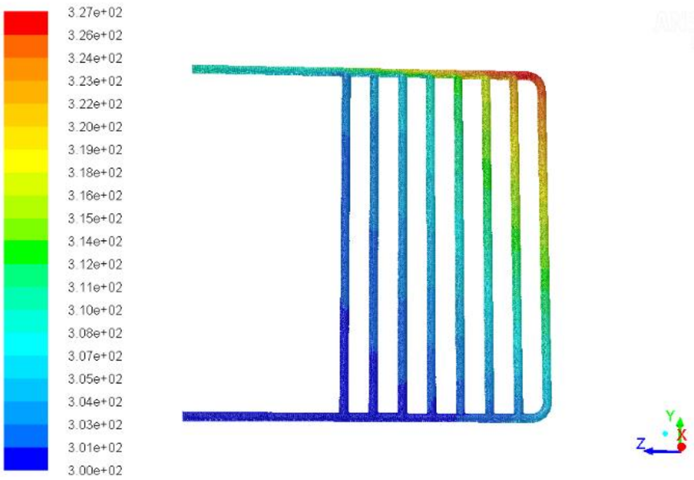

Figure 6. Total temperature contour for riser configuration shown in Figure 2

In the first riser configuration, the water enters through the lower inlet header pipe exits through the outer header pipe. A part of the water entering through the lower header pipe enters the vertical riser tubes. The water entering the left vertical riser tubes are colder than the adjacent right vertical riser tubes. The maximum temperature is obtained at the top right corner of the of riser tube configuration because the water paticle present at the top right corner spend maximum time in the riser tube and the rest of the water do not. The water inside the left riser tube spend minimum time and therefore the temperature of the water inside it has minimum temperature as in the contour of total temperature. The figure 6 depicts the plot of total temperature vs position on the line drawn in upper header pipe for the configuration shown in Figure 2.

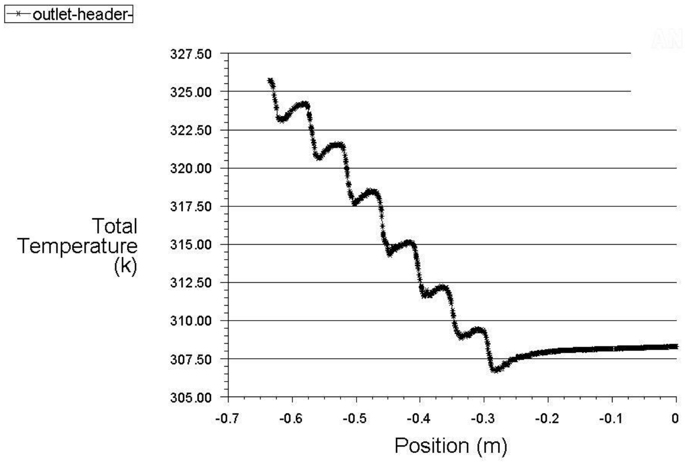

Figure 7.total temperature vs position on the line drawn in upper header pipe for the riser configuration shown in Figure 2

From figure 6 it is evdent that the temperature is maximum at top right corner of the configuration shown in Figure 2. The temperature of the water is further gradually lowered by the cold water coming from the vertical riser pipes. The maximum temperature obtained at the top right corner in the configuration shown in Figure 2 is 327 K. However, the outlet temperature of water from the system is 308 K. Hence, 19 K of the water inside the collector has been lowered by water coming out from the vertical riser tubes.The total temperature contour for the riser configuration shown in Figure 3 has been depicted in figure 7.

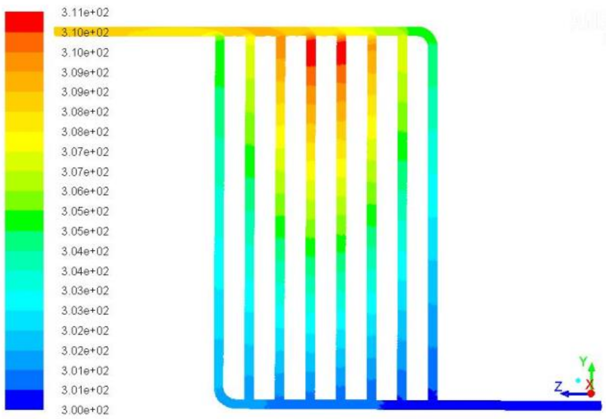

Figure 8 Total temperature contour for the riser configuration shown in Figure 3

From the above total temperature contour it is evident that the maximum temperature obtained is at the top middle portion for the configuration shown in Figure 3. The water enters through the right lower header pipe exiting through the left upper header pipe in this configuration. The velocity of the water is maximum in the extreme left and right vertical riser tubes and it is maximum in the central riser tube and therefore the water in it spend maximum time than the water in other riser tubes. So the temperature is maximum in the central riser tubes at the top mid region.

A line is drawn in the upper header outlet tube in the configuration shown in Figure 3 to examine the temperature variation in the outlet tube. The plot between total temperature and position on the line is shown in figure 8.

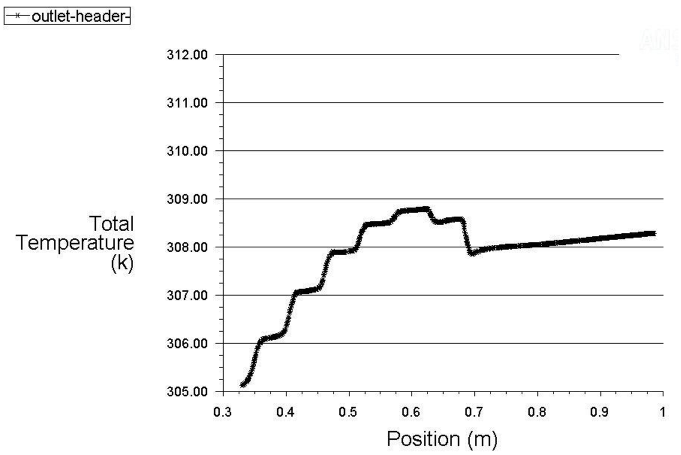

Figure 9. Total temperature vs position on the line drawn in upper header pipe for the riser configuration shown in Figure 3

From the above plot it is event that the maximum temperature of the water obtained is around mid point of the line drawn. Later, the temperature of the water is decreased by the colder water flowing through two riser tubes on the left side of the collector. The maximum temperature of the water obtained in this configuration is 311K. However, outlet temperature of water from collector system is 308.32 K.The total temperature contour for riser configuration shown in Figure 4 has been depicted in figure 9.

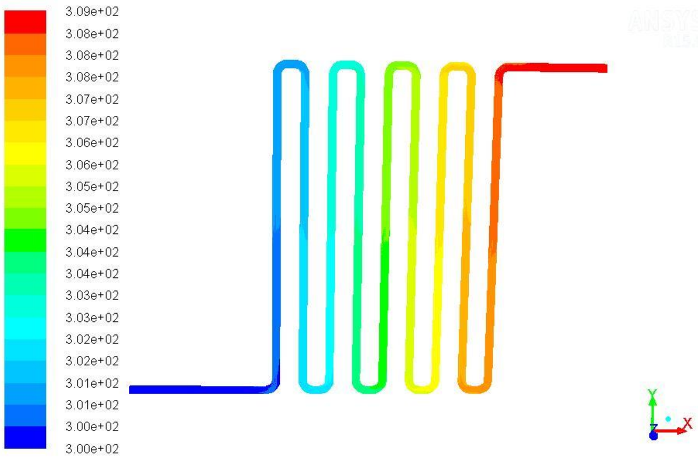

Figure 10. Total temperature contour for riser configuration shown in Figure 4

From the above total temperature contour for riser system shown in Figure 4, it is evident that the maximum temperature of the water insider the riser is obtained at the outlet. The water enters the collector from the lower left pipe and exit it from the upper right pipe. Since the whole configuration of the riser is a single pipe, the velocity of the water flowing inside the riser is almost constant and therefore the maximum temperature is not further lowered by any other colder water coming from the vertical risers as it was the case in the previous two riser configurations. A line was drawn in the upper right header pipe to examine the temperature variation in the pipe. The plot of total temperature vs. position on the line drawn for riser system shown in Figure 4 is depicted in Figure 20.

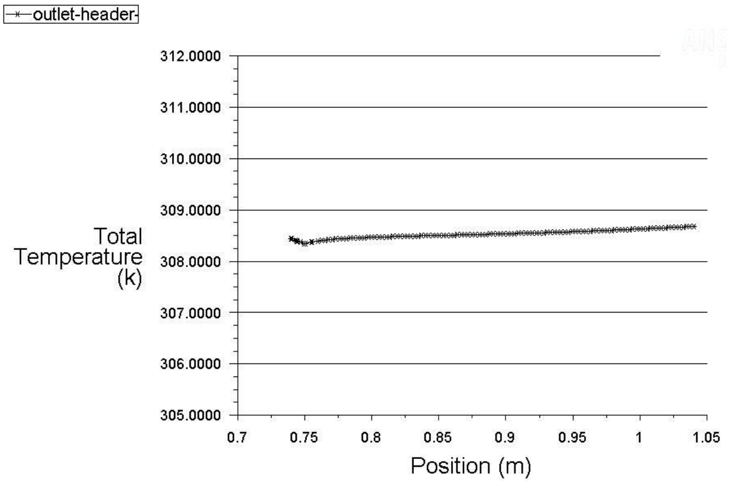

Figure 11. Total temperature vs position on the line drawn in the upper left pipe for riser system shown in Figure 4.

From the plot depcited in Figure 20 between total temperature and position on the line drawn in the upper left pipe for riser system shown in Figure 4. Evident from the figure that the temperature in the upper header pipe is gradually increasing and not altered by any other colder water. The maximum temperature of water in the collector system is obtained in configuration is 308.91 K and it is the temperature outlet of collector which is desirable. The outlet temperature of water is 308.76 K.

In the present work, the temperature contour and the hydraulic impedance among inlet and outlet of water for three different types of riser configurations has been analysed by imposing similar boundary conditions. The pressure dropalong with the outlet temperature and temperature incresae of water for varying mass flow rate for the riser configuration shown in Figure 4 has been analysed and the corresponding graphs have been plotted.

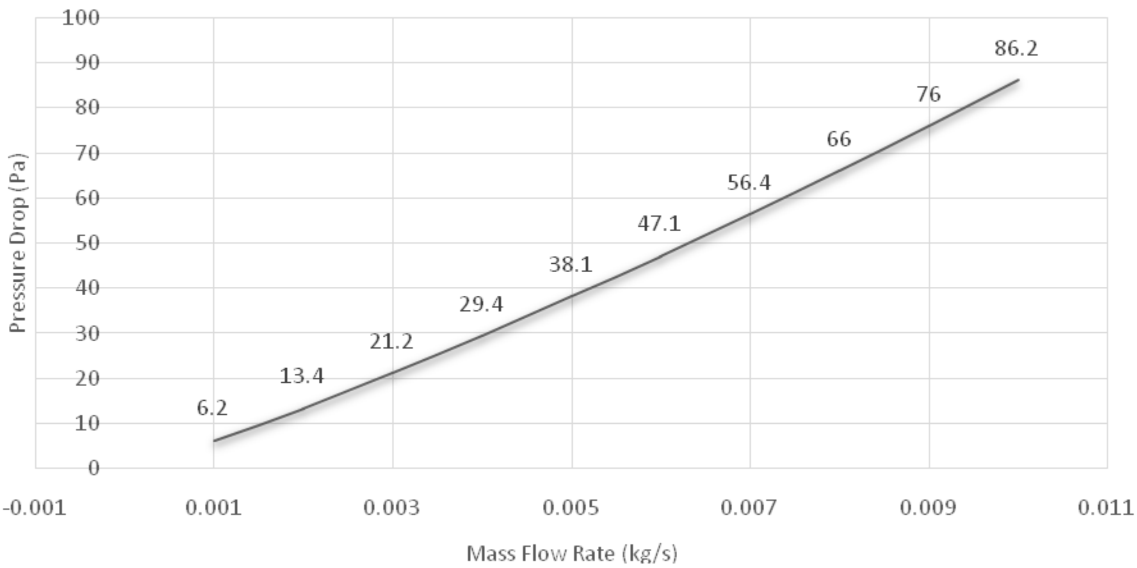

Figure 12. Pressure drop vs mass flow rate of water for the configuration system shown in Figure 4

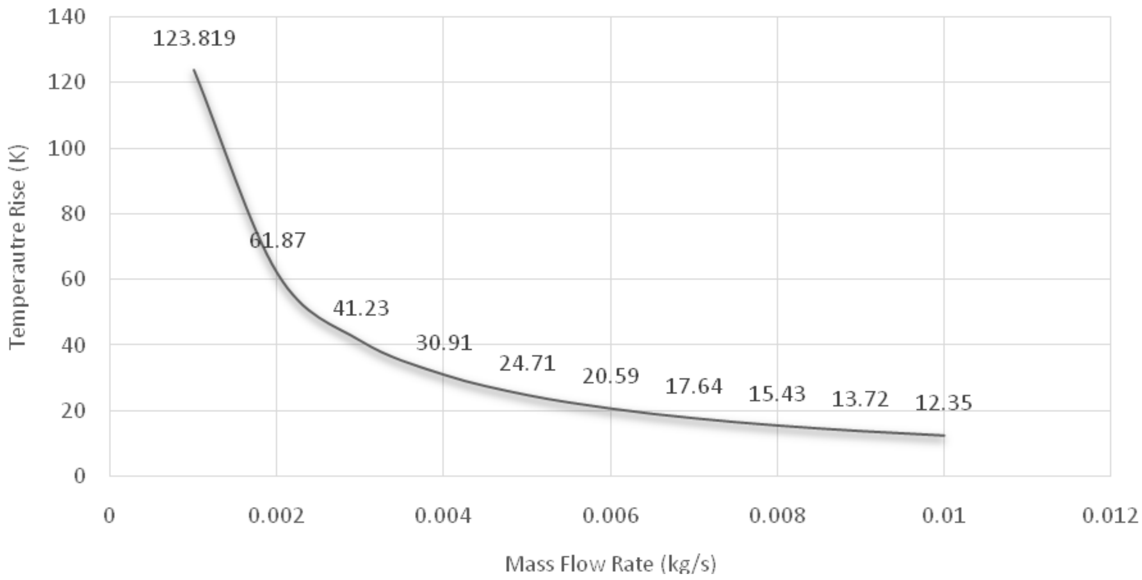

Figure 13. Temperature rise vs mass flow rate for the systematic system shown in Figure 4

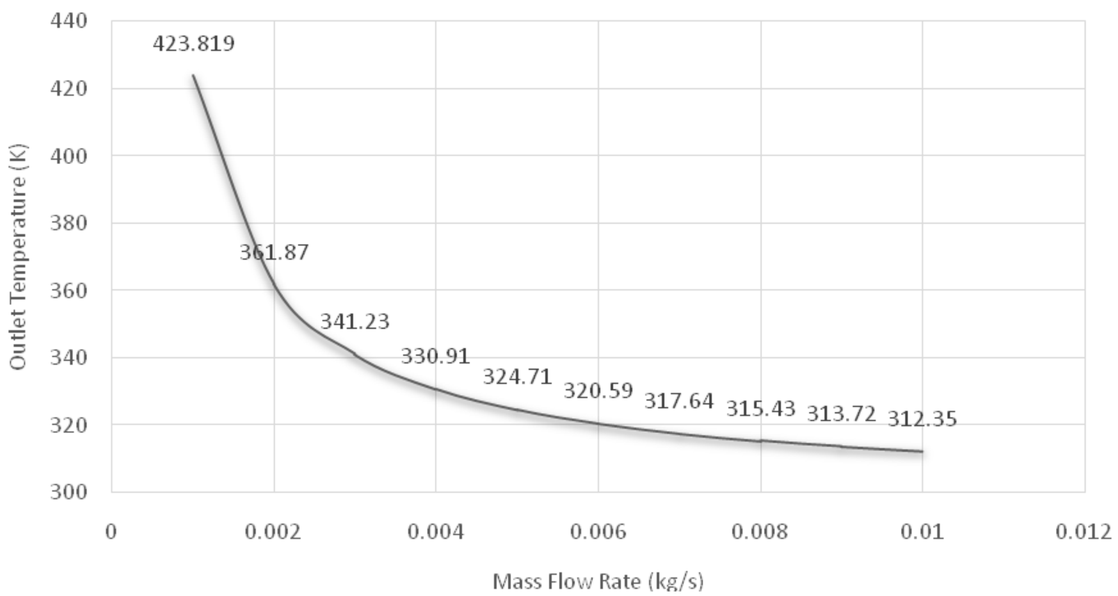

Figure 14. Outlet tempearature vs mass flow rate for the systematic system shown in Figure 4

It is evident from Figure 12 with increase in mass flow rate increases, the pressure drop increses almost linearly. Incrementing the mass flow rate, the velocity of the water flowing through the riser tubes increases as a result of which the frictional losses incresease due to which the pressure drop increases at the outlet of the collector system. On the other hand, increase in temperature i.e. difference between outlet temperature and inlet temperature of the water, increases with the decrease in mass flow rate as shown by Figure 22. This is due to the reason that as mass flow rate decreases, water spends more time in the riser tube as a result of which the outlet temperature of water increases as shown by Figure 23.

4. Conclusion

The thermal and hydraulic performance of solar collector for different riser configurations have been computationally anaysed using CFD software package. The outlet temperature of water for the riser configuration deoicting in Figure 2, Figure 3 and Figure 4 are 308 K, 308.32 K and 308.76 K respectively. Hence, the outlet temperature of water is highest for riser systematic system shown in Figure 4. Therefore, under stated assumptions, riser network shown in Figure 4 is the most suitable riser configuration that can be used for enhacing the thermal performance of the solar collectors.

Assumptions were incorporated while performing computational work, hence, additional work is required in the future direction, which will address the practical challenges involved during modelling the structure of the riser network, for obtaining the most suitable configuration for harnessing solar irradiation.

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