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Computerized Heat Transfer Modeling for Solar Powered Water Purification System

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COMPUTERIZED HEAT TRANSFER MODELLING FOR SOLAR POWERED WATER PURIFICATION SYSTEM

BY

HOUTAN NEYNAVAEE

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Abstract

Since drinkable water resources are limited, as the human population increases it is predicted that providing pure water is a future human challenge. However, a huge resource of the water exists on the earth surface in seas and oceans, which are not proper for drinking and cultivate. Exploiting of a solar powered water purification system is an economy and environment-friendly solution to this human problem.

In this thesis, we present computerized heat transfer model for solar powered water purification system. This Model can be used for calculating the heat transfer, system temperature, and other variable parameters such as boiler pressure, solar collector length, HTF mass flow rate, etc. when the system operating under steady state condition. We modeled system solar collector and boiler using Engineering Equation Solver (EES). System operation was studied under the steady-state condition, and by defining three out of five parameters, vapor mass flowrate, system pressure, heat transfer mass flow rate, solar collector length or boiler coil length, the code can predict the other parameters and properties. Also, we analyzed the outcome data under conditions, and explore effects of the boiler pressure, solar length and flow type on output and system efficiency. Also, we analyzed wind effects on the amount of the absorbed heat by the system. These codes and analysis help engineers to design a water purification system based on their needs. Using the analyses included in this thesis and considering the external parameters such as cost enables them to design their desired water purification system. Based on the analysis that we had done, one recommended design point is, when the system pressure is 0.064 [atm], HTF mass flow rate is 0.2 [kg/s], and solar collector length is 21 [m]. In this case, the vapor mass flow rate, and system COP would be 0.00787 [kg/s], and 91% respectively. These specific numbers are valid for the system geometry that will be discussed in the thesis.

Computerized Heat Transfer modeling for solar powered Water purification system

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Chapter 1: Introduction

This thesis is to develop a model to simulate performance of a solar water purification system. The original system is from a senior project of Santa Clara University Students (Solar Powered Water Purification System 2014). At Santa Clara University, undergraduate students had senior projects for a number of years to design and build a solar-powered water purification system on the small scale, which is portable and easy to use to benefit people in developing country who suffer from lack of the cleaning water. The project Solar Powered Water Purification System 2014 by Jasper Adamek-Bowers, Jamie Anderson, Peyton Harrod, Madison More, and Alexander Thal; was the latest senior project in this area.

Future drinkable water demand is predicted to become a critical issue since the water is one of the most valuable materials for life. According to the USGS water science school reports, 71% of the earth is covered by water, but 96.5 percent of them are oceans. In other words, there is an enormous amount of the water on the surface is brackish water, which is not proper for human uses, or raising plants. [12] In addition, "according to the United Nations, 11% of the people (783 million people) on the earth are living without this commodity". [1] It is estimated that 3.4 million people die annually from water-related illness. Besides, the earth population growth rate is 1.1 percent per year, to provide next generations enough food and water it is necessary to find new sources for this commodity. Also, it is essential to design an economic system that is at the same time environmental friendly. Therefore, the solar powered distillation system is a noble idea for achieving this goal.

The water distillation system is made of different components such as heat exchanger, boiler, parabolic troughs, tracking and control system, photovoltaic panels, vapor, vacuum pump, and Heat Transfer Fluid pump. This system collects the solar power and transfers it to the Heat Transfer Fluid (HTF) which is used to heat the brackish water. The system is shown in Figure 1. The parabolic troughs concentration solar energy on an absorber tube and the absorbed energy increases the HTF temperature. HTF conduct this heat to the boiler to vaporize the salt water in the boiler. Clean steam leaves the boiler and contaminations, and salt remains in the boiler and is flushed out later. The pure water vapor after condensation goes to the drinkable water tank.

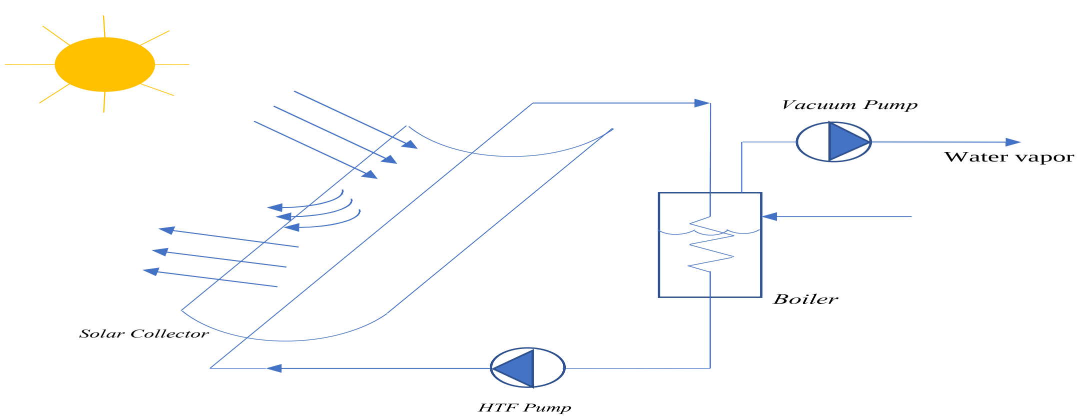

Figure 1. Schematic of vapor distillation system

The team's system accomplished several tasks, though the project was ultimately unable to produce a project goal of 8 gallons of water per day. [1] "Teams in Santa Clara University made some modification to achieve this gain." They determined that the most efficient and profitable reflectors are parabolic troughs and Fresnel reflector arrays leading solutions in the industry at this time. Parabolic troughs are an established technology, and function by transmitting energy to a pipe running along the mirror's focal point. Linear Fresnel reflectors are an emerging energy solution, similar to the parabolic trough, that consist of an array of mirrors working in tandem to focus solar thermal energy on a particular point. [1] The group choose parabolic troughs, as they are cheaper and more efficient. Instead of heating water directly by solar energy, the system heats the Heat Transfer Fluid which is Duratherm 450.The heat transfer fluid moves the heat from more delicate absorber tube to a heat exchanger that can more easily deal with the corrosive brackish water. Duratherm 450 is an environmentally friendly, non-toxic, and non-hazardous liquid, which is design for heating applications up to 232 ºC. To maximizing energy absorption, a one-inch copper tube was sprayed by a black paint chosen as the receiver. The boiler is a pressure vessel that received the heat transfer fluid through a three-eighths inch copper pipe was formed into a helical coil and immersed into the boiler water to act as an evaporator loop to transfer the absorbed energy by HTF to the boiler to evaporate the water in the pressure vessel.

To point the parabolic trough the group used solar tracking controller, and a motor to actuate the troughs. Therefore, we always have parallel sun irradiation to the troughs. There are multiple pumps used, one to circulate the heat transfer fluid, the other one which is a vacuum pump to set a system pressure below atmospheric pressure. This enables the system to evaporate water at a temperature under 100 °C. A third pump is used to circulate the clean water vapor to the condenser. A solenoid valve was used to regulate refilling the brackish water into the active system.

This thesis is an extension of the previous work with the intention of building a computational model. This model can be used to calculate the heat transfer, system temperature, and other variables for different design conditions. This model can then be used to vary parameters and understand the system performance. This will be useful to determine a suitable design of the system such as boiler coil length, solar collector receiver length or vacuum pump to provide proper boiler pressure. Also, we are capable of designing a system for desire clean water. Besides, we are able to study the effect of increasing HTF flowrate on the system.

To change the mass flowrate of HTF a variable speed circulation pump (Oberdorfer N991-32 gear pump) was used and was controlled by an external pulse width modulation (PWM) motor driver (CanaKit UK1130). The PWM driver was employed by varying two potentiometers that controlled the frequency and duty cycle of the voltage signal. [1]

In terms of the design analysis several questions are considered. What would happen if we change the HTF flowrate? Does, it affects the design of the solar collector? How much would the mass flowrate of purified water change if we change HTF mass flowrate? How effective is our system if we change our boiler pressure? What if we demand the cleaner water? Is it possible to measure the coil surface temperature in the different situations? In this paper, we model the system to answer these questions. We study our system under various situations. For solving these problems and further design, Engineering Equation Solver (EES [9]) was used. This software system allows the user to inset a system of equations and look up material parameters. The equations can be written in a direct form and the software identifies the variable that need to be solved for. Then it solves the system in an interative approach. To determine that the correct solution is arrived at among multiple possible solutions, the software allows the user to specify allowable ranges for the variables. This allows a realistic solution to be arrived at. EES will help us if one parameter is changed how other parameters would change.

Chapter 2: System Description and Constraints

The system purifies water with the aid of solar energy. The solar collector absorbs heat, transfers it to the HTF, and increases the exit temperature. Water in the boiler removes the heat from the HTF that had been absorbed, and it caused vaporization of the brackish water when the water in the boiler is raised to its saturation temperature which is comply with the boiler pressure. The water vapor is condensed in the condenser and provides the clean water while the salt remained into the boiler. In the solar collector, the incident radiation on the trough is reflected to its focal point, where the receiver pipe is located. To increase the absorptivity, the receiver pipe has a black paint coating on its surface. Therefore, there is no heat lost through reflection from receiver pipe surface wall. The emission is higher with the black surface, but the surface area of the pipe is less than the projected surface area of the trough. Therefore, amount of incoming heat is much larger than the emitting heat from the pipe surface. Additionally, the convective heat transfer to the environment is also calculated. This can be either from natural convection or forced convection if a wind is blowing. Both conditions are calculated in the solar collector analysis by itself. However, all of the preliminary results are based on neglecting the wind effect. A calculation is done illustrating the loss when wind blows past the receiver tube.

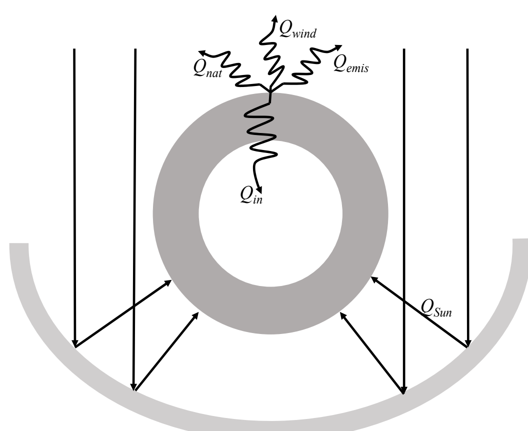

Figure 2. Schematic picture of heat distribution on the solar collector

Figure 2 shows a cross-section of the solar collector. Based on the first law of thermodynamics the heat transferred to the receiver pipe is transmitted into the working fluid or emitted as a loss to the surroundings. The heat input increases the pipe temperature. Based on the new pipe temperature, heat is emitted to the surrounding environment as radiation. Because the pipe wall temperature is higher than the ambient temperature, there is also a natural convection heat transfer that causes losing heat to the surroundings. However, in the presence of the wind, the amount of the heat lost increased and a forced convection mode exists. The amount of the heat that has not been removed from the pipe surface by either radiation or convection would transfer to the HTF by convection. This heat in Figure 3 adds HTF temperature up. HTF transfer the absorbed heat to the boiler to use it for vaporizing brackish water and increasing the inlet water temperature to its saturation temperature that complies with the boiler pressure. For steady state, all the absorbed heat should be transferred to the brackish water in the boiler.

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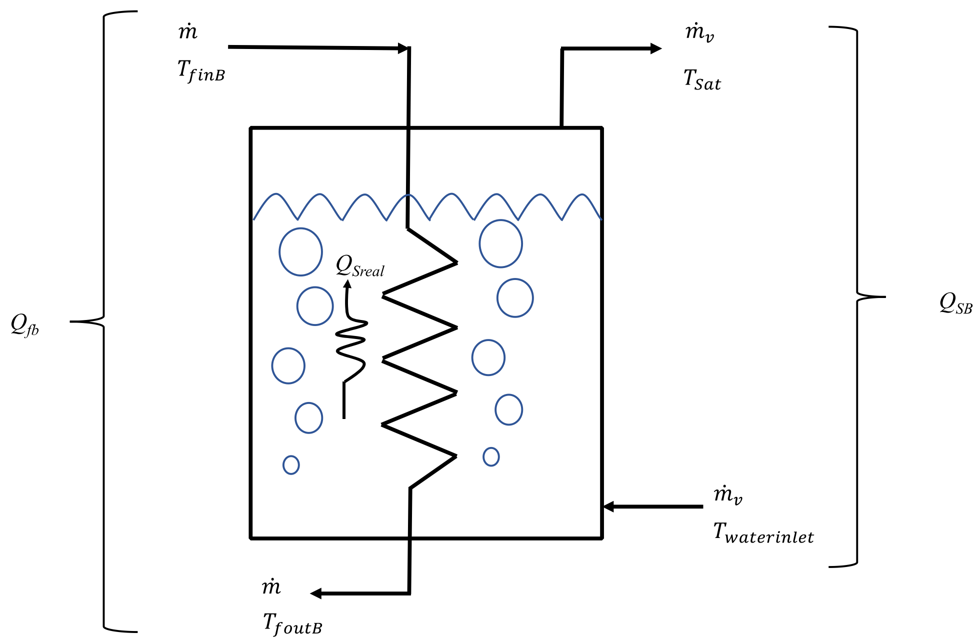

Figure 3. Schematic picture of heat distribution in the boiler

The previous design was limited to one specific geometric system; however, with this code, we are capable of designing a system under various situations in on our range of study, which is wide enough for design proposes. In addition, system changes are predictable when one of the parameters changes. Ultimately, we would like to understand the effect of specific parameters in the system efficiency.

One constraint of the analysis is that the system is quasi-steady. This means that even while the ambient temperature and radiation over the daytime are variable we consider the system to be in equilibrium at any given time. We realize that at the beginning of the day, the receiver pipe temperature is close to ambient temperature, and it takes time to get to the steady state temperature, but for a first level analysis, assuming the system is quasi-steady and we will generate ideal performance curves. Water temperature in the boiler at system start-up is lower than the saturation temperature. Therefore, it takes time to water temperature reaches to its saturation temperature.

To have the nucleate boiling in the boiler there needs to be substantial heat input in the receiver pipe therefore the flow has to be turbulent. Hence, the HTF flow in the boiler coil has to have the Re more than 2500. To reach to this kind of the flow, we have a limitation in choosing the HTF flowrate. In addition, because in this thesis we are not studying the condenser we need to assume a constant temperature of the inlet water at the boiler.

Assumptions

assumptions. Some of these assumptions are based on student work that has been done earlier. For instance, they have used trough with an aperture width of 39.5 inches. [3] "It needed to be manufactured to be highly reflective and as possible choices: mylar, acrylic mirror, ReflecTech (Arvada, CO) mirror film, and Clear Dome Solar (San Diego, CA) Parabolic Reflectors". Thus, we assume it has a reflectivity equal to one. Also, they sprayed the receiver pipe black. Hence, we assume it as a black body. The mean solar irradiation on the earth is 1000 [W/m^2]. We assume the boiler is insulated and we do not have heat loss through the boiler wall to the surrounding environment. We also assume that we turbulent flow in the boiler coil. Therefore, we have limitations on mass flowrate that cannot be less than 0.024 [kg/s]. it is assumed that the temperature of the receiver pipe is uniform. Therefore, we are able to calculate the natural convection and irradiation for receiver pipe easier. Also, the assumption is made that the receiver pipe was installed with 20 degrees to the flat earth. It is assumed that we do not have heat loss between the solar collector and boiler. Given the rates involved in this system a quasi-steady state is a reasonable assumption. In this work, the situations are studied under steady-state condition. Thus, we neglect the start-up conditions and changes over the daytime. That means we consider the system for a couple of hours to heat the system up to increase the sea water temperature in the boiler to saturation temperature, temperature of the receiver pipe gets stabilized, and neglect variations over long period of the time. Additionally, we want all the thermal power, which is absorbed in the solar collector transfer to the brackish water in the boiler. Also, it is assumed that solar irradiation and ambient temperature are constant during a day. We used Duratherm© 450 as Heat Transfer Fluid which its properties attached into the appendix. In addition, we assume that the difference temperature between the outer surface wall of the boiler coil and saturate temperature of the water at boiler pressure is more than 30ºC. Hence, we will have nucleate boiling. In order to solve each component independently, we had to made reasonable temperature assumptions at inlet and outlet of that specific component. For instance, the HTF temperature at inlet of the solar collector and boiler are 40 ºC, and 128.6 ºC respectively. Solar collector receiver pipe is made of the 1-inch copper pipe, which is painted black. The boiler shell is manufactured from an aluminum sheet with 0.00635 [m] thickness, and its helical coil in the boiler is a 3/8-inch copper pipe.

When all components are solved independently to synchronize them together, we allow the system to solve for the inlet and exit temperatures of the heat transfer fluid and these temperatures need to be consistent for both components by removing the assumptions and making the assumed temperatures, which are connected to each other, equal.

Unsteady Condition Estimate

In this thesis, we claim that a day time is long enough that system can reach to the steady state condition and able to operate in the steady state conditions for hours. Therefore, a case study is done on one recommended condition to estimate the required time for the system to reach the steady-state condition. The case study is for the system when the HTF mass flow rate is 0.2 [kg/s], and the Boiler pressure is 0.07 [atm]. Some required parameters can be extracted from Table 21 and the required material characteristic is given as follows:

Copper Specific heat capacity: C_{PCU} = 384.4 [J/kg K]

Aluminum specific heat capacity: C_{pAl} = 904 [J/kg K]
Copper density: ρ_{CU} = 8960 [kg/m^3]
Aluminum density: ρ_{Al} = 2700 [kg/m^3]
Water density from Table 21: ρ_w = 912.5 [kg/m^3]

We Assume the entire system as a bulk volume and use the energy conservation equation to compute the required time for the whole system to reach the steady state condition.

$$(\overline{\rho\ V\ C_P})\frac{\overline{\Delta T}}{\Delta t} = \ \dot{Q}_{in} - \dot{m}h_{fg} \quad (2\text{-}1)$$

We need to find the volume for all system components in to find the $\overline{\rho\ V\ C_P}$. In order to find $\overline{\rho\ V\ C_P}$. It is necessary to calculate $\rho\ V\ C_P$ for each component separately and at the end add them up.

Inner diameter of the 1-inch pipe: D_1 =1 [in]=0.0254 [m]
Outer Diameter of the 1-inch Pipe: D_2 = 1.24 [in]= 0.03149 [m]

Inner diameter of the 3/8-inch pipe: D_{1coil} =0.375 [in] = 0.009525 [m]
Outer Diameter of the 3/8-inch Pipe: D_{2coil} =0.5 [in] = 0.0127 [m]

For calculating volume of the copper in the system:

$$V_{CU} = \left[{D_2}^2 - {D_1}^2\right]\frac{\pi}{4}\ L + \left[{D_{2coil}}^2 - {D_{1coil}}^2\right]\frac{\pi}{4}L_{Coil} \quad (2\text{-}2)$$

For finding the HTF volume:

$$V_{HTF} = \frac{\pi}{4}\ [{D_1}^2L + {D_{1coil}}^2L_{coil}] \quad (2\text{-}3)$$

For computing aluminum and water volume it is necessary to design a boiler that can contain the helical coil, which is sunk in the water with a space volume above the water level for water vapor and air. In order to design the boiler, it is essential to find the total required height for helical coil. The total height of the helical coil is computed as follow:

$$H_T = N\ H \quad (2\text{-}5)$$

$$N = \frac{L_{coil}}{L_U} \quad (2\text{-}6)$$

$$L_U = (H^2 + C^2)^{0.5} \quad (2\text{-}7)$$

$$H = 2.5\ D_{2coil} \quad (2\text{-}8)$$

$$C = \pi\ D_{loop} \quad (2\text{-}9)$$

N: Number of the loop
H: rise for each loop
L_U: required length for each loop
D_{loop}: diameter of each loop

By using equations (2-5) to (2-9) we gain the total required height approximately 39 [cm] and to make further calculation easier we chose 40 [cm] as it is shows in Figure 5 with other dimensions.

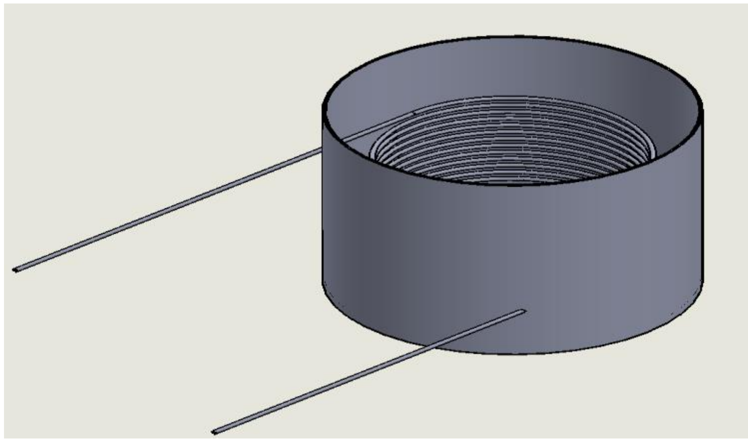

Figure 4: isometric view of the Boiler

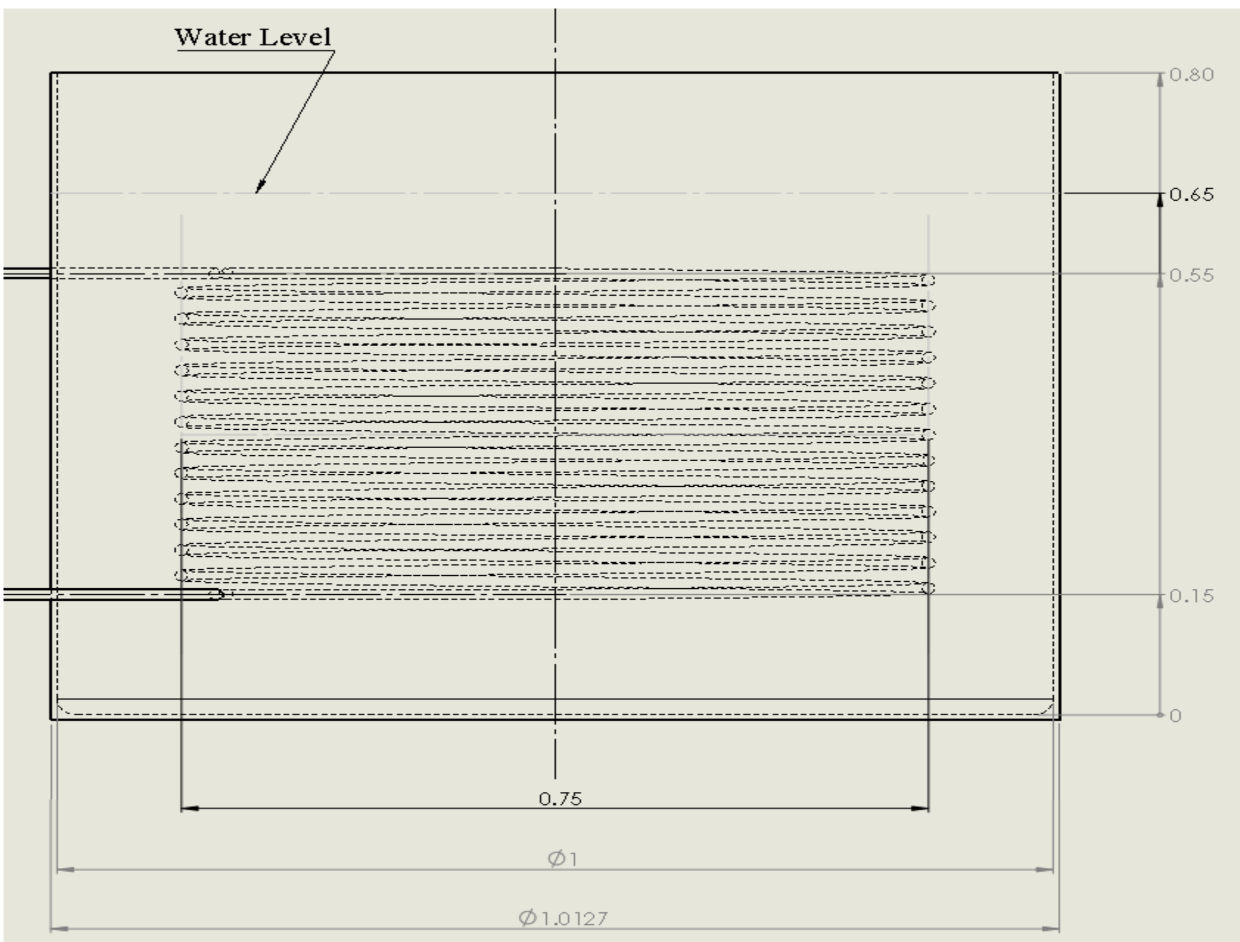

Figure 5: Designed Boiler for System with absorbed heat 10.429 [kw] and boiler pressure 0.7 [atm]

Based on the dimensions that is shown in Figure 5, the volume of water in the system is calculated as follows:

$$V_{water} = \frac{H_{water}\,\pi\,D_{1boiler}^2}{4} - \frac{\pi\,D_{2coil}^2\,L_{Coil}}{4} \tag{2-10}$$

where H_{water} is the water height level and $D_{1boiler}$ is inner diameter of the boiler shell, which in this case is 1 [m].

Since the thickness of the boiler shell wall in 0.00635 [m] and we are assuming the boiler lid is as thick as the shell wall, the aluminum volume in the system can be find by:

$$V_{Al} = \frac{\pi}{4}\,H_{Al}\left(D_{2boiler}{}^2 - D_{1boiler}{}^2\right) + 2\,\frac{\pi}{4}\;x_{boiler}D_{2boiler}{}^2 \tag{2-11}$$

where H_{Al}, $D_{2boiler}$, and x_{boiler} are height, outer diameter, and thickness of the boiler respectively.

Using all the volumes, we find the $\rho\,V\,C$ for each component separately and add them up:

$$\overline{\rho V C} = \rho_{Al}V_{Al}C_{PAl} + \rho_{CU}V_{CU}C_{PCU} + \rho_{W}V_{W}C_{PW} + \rho_{HTF}V_{HTF}C_{PHTF} \tag{2-12}$$

$\overline{\Delta T}$ in Equation (2-1) is the temperature difference between average operating temperature and average starting temperature in the morning for the entire system. Average starting temperature is the temperature of the system at morning before it starts the work. The average starting temperature is assumed 30[°C]. The average operating temperature is an average of all components temperature when the system operates under steady state condition. These temperatures could be found in Table 21.

Although the trough rotates with the sun movement to absorb the maximum solar radiation during a day, there is a radiation variance during a day time, the amount of the absorbed heat in the morning is less than the noon because of the atmosphere thickness. For this case study, it is assumed the absorbed heat by the system is 85 percent of the steady state condition. At the same time $\dot{m}h_{fg}$ is estimated to be half of the absorbed heat in the morning because we assumed that part of the input into the system is to reach to the steady state condition. Therefore, it takes about 3 hours and 27 minutes for the system to reach the steady state condition when the boiler pressure is 0.7 [atm], and the HTF mass flow rate is 0.2 [kg/s] by using equation (2-1). Hence, our first claim is valid for particular condition, and system reaches to steady state condition during a day. Remember all this calculation are valid for the system that geometry has been mentioned earlier.

Chapter 2: Modeling Approach

To measure all project factors at the beginning, we break the whole system into separate components and then study each component individually. We study the system based on the assumptions that we made, and apply firs law of thermodynamics to compute the system unknowns. In this thesis, we will only model two components: the solar collector and the boiler. They are two key components in system operation, and will be shown their performance in terms of temperature, pressure, and other design parameters. They also allow us to study the coupling of the components for overall performance analysis. In follow-on work the model can be extended to include the condenser, transient analysis, and more realistic assumptions.

Solar Collector

At the solar collector, we are interested in the heat which is absorbed by HTF. The solar collector is a parabolic mirrored trough with a receiver tube which is located at the trough focal point. The receiver tube has heat transfer fluid passing through it and it is painted black. We need to look at the heat transfer from two sides of the view. First, the heat that comes from the solar and after the losses goes to the HTF. The following equation calculates this amount of heat:

$$Q_{in} = Q_{sun} - Q_{emis} - Q_{nat} - Q_{wind} \tag{1}$$

where Q_{in} is the heat that is absorbed by the system in solar collector. Q_{sun} is the real heat which comes from the sun and irradiated on the mirror and reflected and absorbed by surface of the receiver pipe (mirrored trough reflectivity and absorptivity of the receiver pipe are assumed one). Q_{emis} is the emissive power which receiver losses by radiating to the surrounding environment. Q_{nat} is the heat loss through the natural convection, Q_{wind} is additional heat lost because of the wind.

The mean solar irradiation on the earth surface is 1000 [W/m^2]. Q_{sun} depends on the absorptivity of the mirror which we assumed to be equal to 1. Also, because the surface of the receiver has black color and we assumed it as a black body the emissivity (ε) is equal to 1. Based on the Kirchhoff's law the emissivity is equal to the absorptivity,

$$\dot{Q}_{sun} = 1000\ \rho\ \varepsilon\ A_{mirror} \tag{2}$$

$$A_{mirror} = W_{app}\ L_{pipe} \tag{3}$$

where the W_{app} is the width of the aperture and L_{pipe} is the length of the mirror which is equal to the longitude of the receiver pipe.

While the temperature of the receiver pipe increases and goes above the temperature of the environment it starts to loss heat by radiation. This heat in this paper is shown as Q_{emis} and we can find it by:

$$Q_{emis} = A_{pipe}\ \varepsilon\ \sigma\ (T_{osur}^4 - T_{amb}^4) \tag{4}$$

Stefan–Boltzmann Constant: $\sigma = 5.67.10^{-8}\ [\frac{W}{m^2K^4}]$

T_{osur} is the temperature on the outer wall surface of the receiver pipe, and T_{amb} is the ambient temperature. A_{pipe} is outer surface area of the receiver pipe. As we assumed the receiver as a black body the reflectivity is zero. Remember the temperature of the receiver pipe was assumed to be uniform. Also, heat could be lost by natural convection. This amount of heat is computable by:

$$Q_{nat} = A_{pipe}\, h_w\, (T_{osur} - T_{amb}) \tag{5}$$

h_w is convection heat transfer coefficient by natural convection and it is computed by:

$$h_w = \frac{0.524\, k\, (Ra_L)^{\frac{1}{4}}}{L} \tag{6}$$

$$Ra_L = \frac{g\, \beta cos(\theta) \Delta T\, L\text{^}3}{\alpha \nu} \tag{7}$$

$$\Delta T = T_{osur} - T_{amb} \tag{8}$$

$$T_{avg} = \frac{T_{osur}+T_{amb}}{2} \tag{9}$$

g: gravity
β: Expansion coefficient ($1/T_{avg}$)
α: Thermal Diffusion rate of air at average Temperature
L: length of the receiver pipe.
ν : Kinematic viscosity of air at T_{avg}
θ : 70º, angle between receiver and normal vector to the earth
K: Conduction heat transfer coefficient of the air at T_{avg}
Ra_L: Rayleigh number for length of the receiver tube.

Now we need to calculate the heat loss in present of the wind. We consider this as an additional heat lost above that generated by natural convection. We are capable to find this heat by:

$$Q_{wind} = A_{pipe}\, h_{wind}\, (T_{osur} - T_{amb}) \tag{10}$$

$$h_{wind} = \frac{NU_{Dwind}\, k_{air}}{D_{pipe}} \tag{11}$$

$$Re_{D\,wind} = \frac{V_{wind}\, D_{pipe}}{\nu} \tag{12}$$

Zukauskas relation:

$$NU_{Dwind} = C\, Re_{DWind}^{m}\, Pr^{n}\, (\frac{Pr}{Pr_s})^{\frac{1}{4}} \tag{13}$$

C is constant of Zukauskas equation that is extract from Table 22 which is included in the Appendix.
h_{wind}: convection heat transfer coefficient for force convection by the wind.
NU_{Dwind}: Nusselt number for wind forced heat transfer
k_{air}: conduction heat transfer coefficient of air on $T_{avg.}$
$Re_{D\,Wind}$: Reynolds of the wind on the outer receiver pipe surface
V_{wind}: Wind velocity [m/s]

D_{pipe}: outer receiver pipe diameter
Pr: Air Prandtle number at ambient temperature

For the Zukauskas relation all properties except Pr_s, are evaluated at ambient temperature, which is assumed 20 ºC. Pr_s is evaluated at receiver outer surface wall temperature.

Now using the first law of thermodynamics, all the heats that absorbed by the receiver pipe has to be transferred to the inside the pipe and into the HTF.

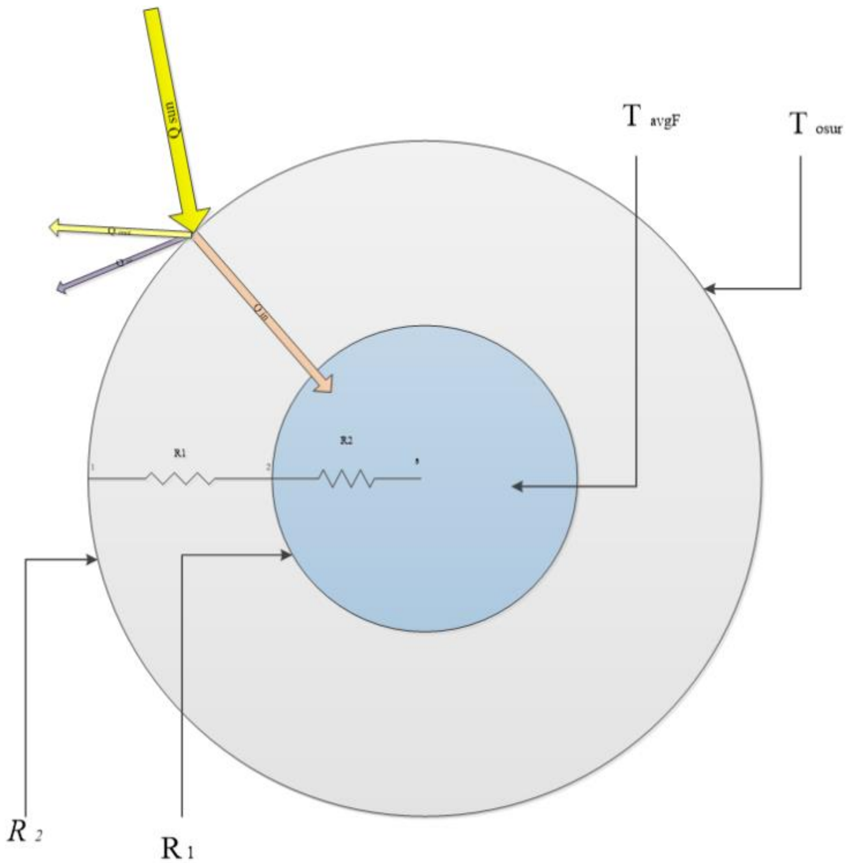

Figure 6. Solar Collector receiver pipe schematic

$$Q_{cond} = \frac{T_{osur} - T_{avgF}}{R_{total}} \tag{14}$$

$$R_{total} = \frac{ln(\frac{r_2}{r_1})}{2\,\Pi L\,K_{pipe}} + \frac{1}{2\Pi r_1\,L\,hf} \tag{15}$$

where T_{avgF} is average temperature between, temperature of HTF at Solar collector inlet and outlet. r_1 and r_2 are outer and inner radii of the pipe respectively. k_{pipe} is the conduction heat transfer coefficient for copper since the receiver tube made of copper. Because we study the system based on two types of flow, laminar and turbulent, the way to determine h_f is different. The following shows the formula for finding h_f for each flow type in the solar collector. While the flow in the Solar Collector is laminar:

$$h_f = 3.66 \frac{k_f}{D_1} \tag{16}$$

When the HTF mass flowrate becomes greater than 0.1766 [kg/s], the flow at solar collector changed to turbulent flow, and it is computed by:

$$h_f = 0.023\, Re_F^{\frac{3}{4}}\, Pr^{0.4}\, \frac{k_f}{D_1} \tag{17}$$

$$Re_F = \frac{\dot{m}\, D_1}{2\, \pi\, r_1^2\, \mu_f} \tag{18}$$

$$Pr_f = \frac{c_{Pf}\, \mu_f}{k_f} \tag{19}$$

D_1 and r_1 *are i*nner diameter and radius of the solar collector receiver pipe respectively. k_f, C_{Pf}, and μ_f are thermal conductivity, heat capacity, and dynamic viscosity of Duratherm 450 respectively.

Finding HTF Properties

It is necessary to have the HTF properties to find the unknown variables. The thermal HTF properties depend on the temperature, which is varies for different calculations. The software calculates the unknown parameters based on the initial guess values. The calculation is done and parameters are known if the equations converge; otherwise, a new guess value would be picked by software based on the residual. The new guess value for HTF temperature requires new HTF properties, which are appropriate for the new temperature. Hence, it is essential to create a temperature dependent function for each property that make software able to call that property for any temperature. These formulas allow the software to extract correct values for each of the HTF properties with a guess temperature and check if the result converges. Remember that the Duratherm properties should be function of temperature. These formulas attached in to the appendix.

In following pages, we compare the measured property values above with the amount we found by these best-fit relations. To find these equations, we use EES.

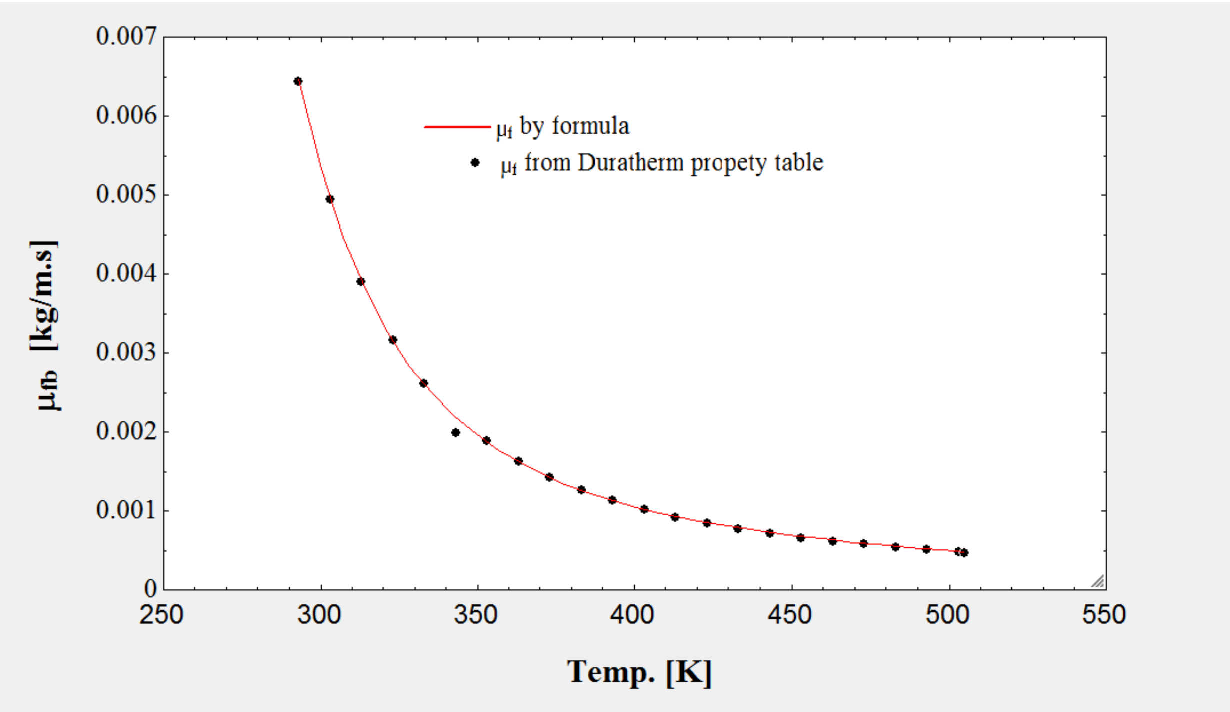

Figure 7. Compare dynamic viscosity for Duratherm 450 obtained by experimental measurement vs. formula

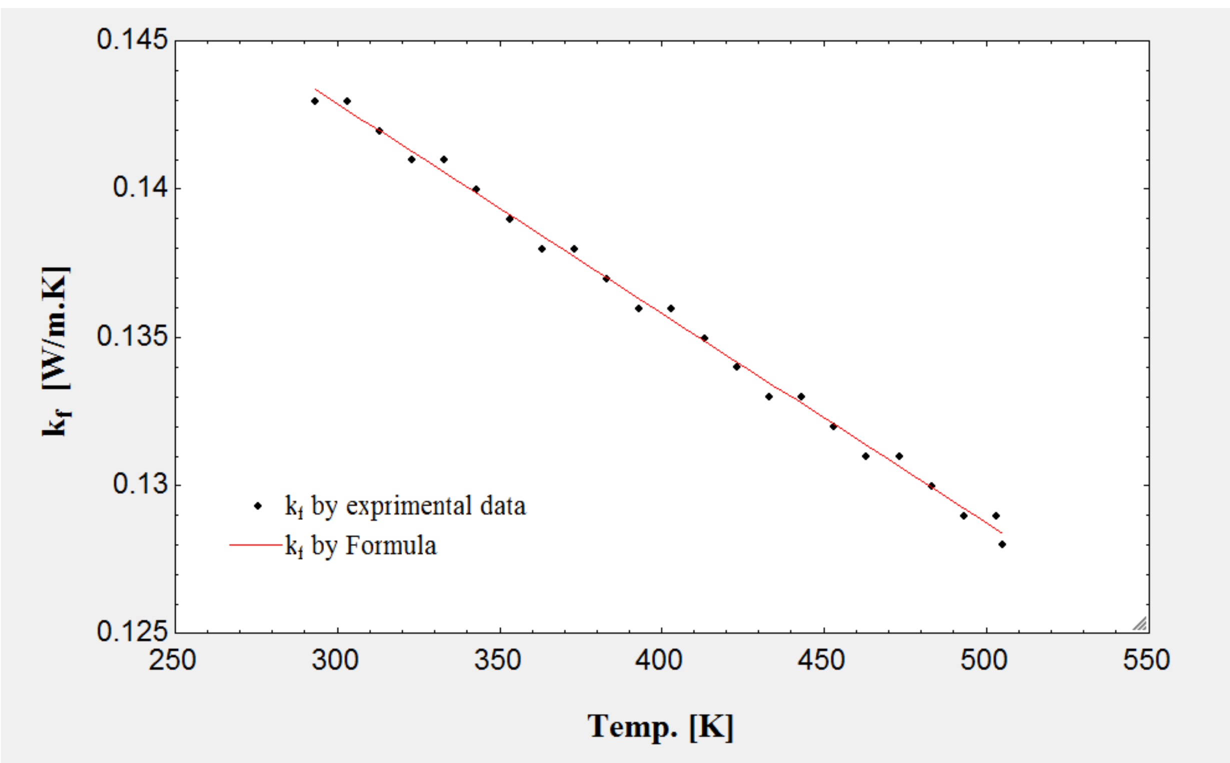

Figure 8. Compare conductivity coefficient for Duratherm 450 obtained by experimental measurement vs. formula

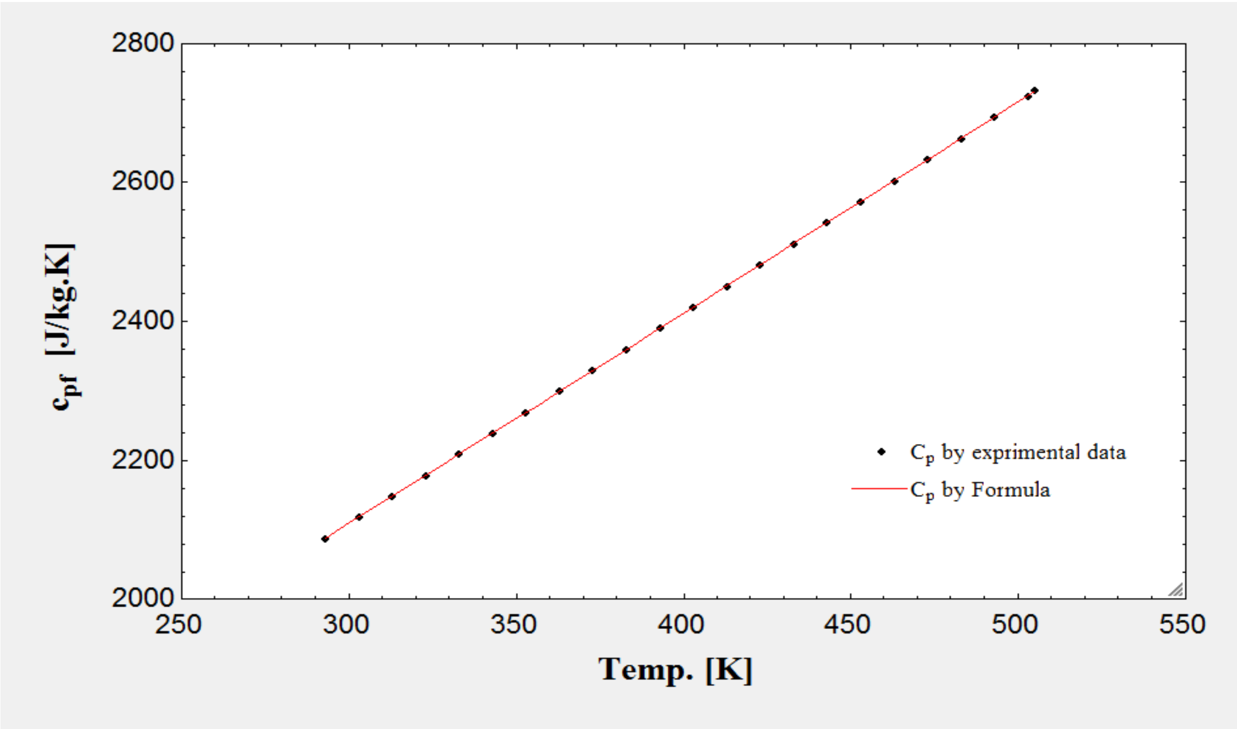

Figure 9. Compare heat capacity for Duratherm 450 obtained by experimental measurement vs. formula

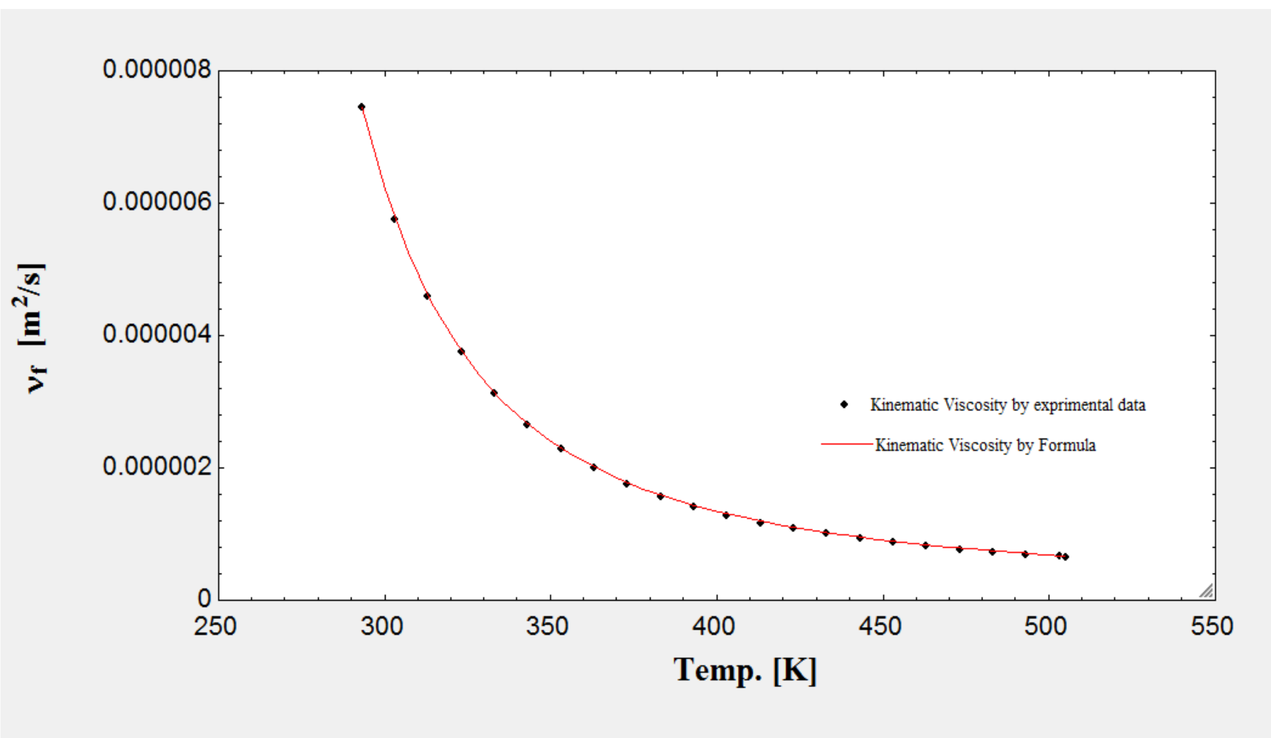

Figure 10. Compare Kinematic viscosity for Duratherm 450 obtained by experimental measurement vs. formula.

Absorbed Heat and Heat Balance in Solar Collector:

The heat that transferred to the HTF will cause the temperature increase from the inlet to the exit. This heat balance is given by:

$$Q_f = \dot{m}\, C_{pf}\, \Delta T \qquad (20)$$

where ṁ is the HTF mass flowrate, which pass through the solar receiver pipe. If we assume that the inlet temperature of the HTF is 40ºC therefore, by using energy conservation law, we are able to calculate the heat flux balance, and the results of Equations 1, 14, and 20 are equal to each other. By this technique, we can calculate all the unknown quantities.

$$Q_{in} = Q_{cond} = Q_f \qquad (21)$$

Comparison of the wind effect on absorbing Heat by HTF in the Solar Collector:

The goal of this project is to determine the effective design of a solar receiver and evaporator. On the following pages, we have the table that calculates the performance on the solar collector while we change the length of receiver pipe, and consequently the length of the reflector.

Also, we compare the heat which is absorbed by HTF with the same length of the receiver with and without wind correction. We found out that the absorbed heat without wind is almost two times bigger than the absorbed heat when the receiver is exposed to the wind with 6 [m/s] (about 21 [km/hr]) speed when the ambient temperature is 20 ºC. This is consistent with experimental observations in the previous work.

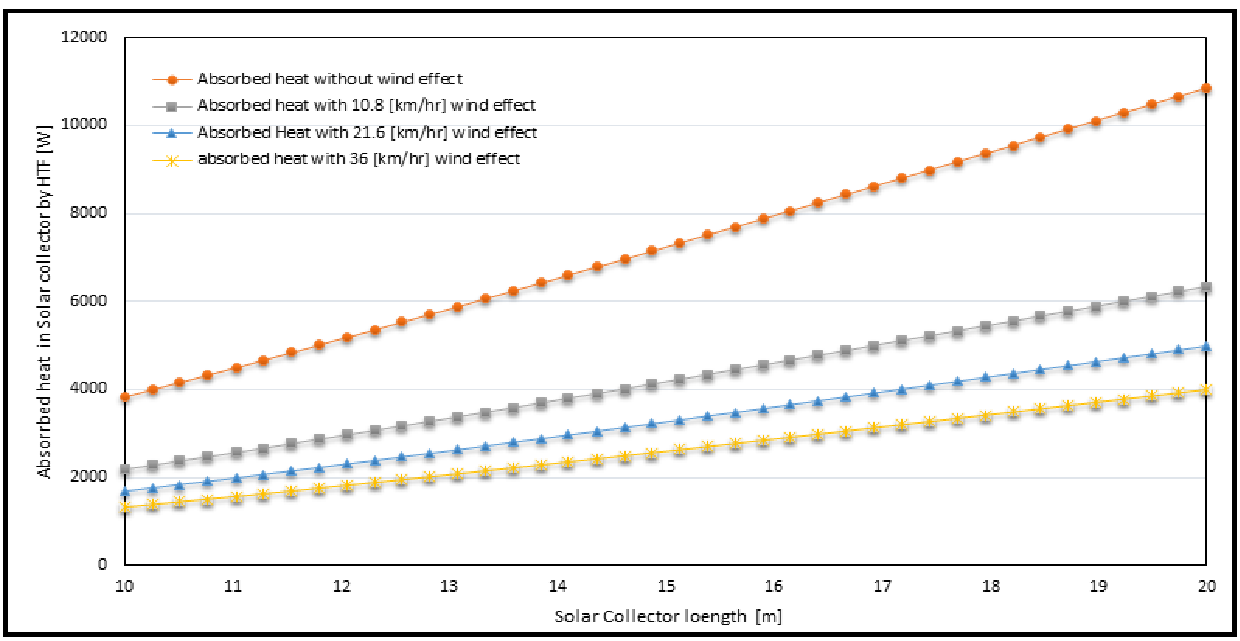

Figure 11. Compare absorbed heat by HTF in the solar collector vs. the solar collector receiver pipe length with different wind speed and without wind

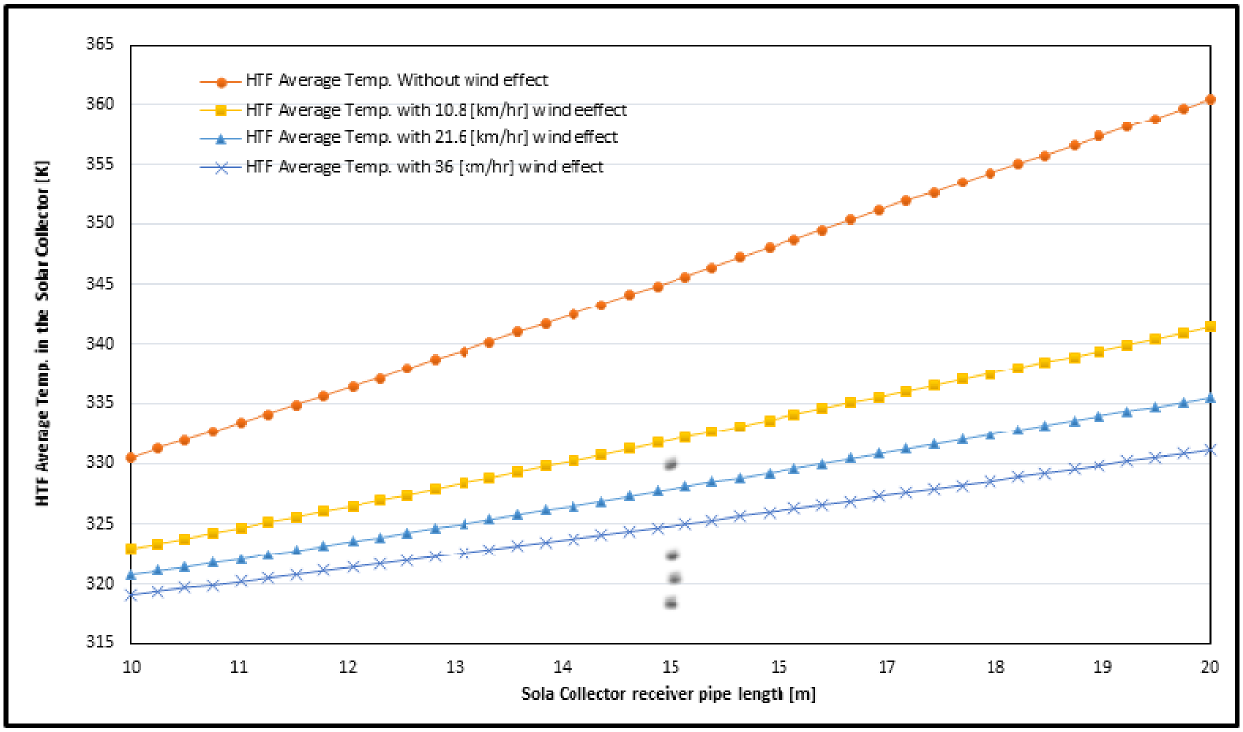

Figure 12. HTF average temperature in the solar collector vs. the solar collector receiver pipe length with different wind speed and without wind

By comparing the wind effects on the system, we recognized the percentage of heat lost by increasing the receiver pipe length increased. While we increase the pipe length to absorb more heat, the amount of the heat lost increases too. In the other word, there is a direct relation between the amount of the absorbed heat and heat lost in solar collector. Because a longer receiver means that it is at a higher mean temperature, and the convective loss is related to the difference in the receiver temperature and surrounding temperature. However, the ratio of the heat lost to the absorbed heat while the receiver length increase significantly is higher than the same ratio when there is no wind. It could be observed that the graph slope of absorbed heat without the wind effect is sharper than the absorbed heat graph. Hence, the efficiency of the system drops faster while the receiver length increases in present of the wind.

Boiler

In this section of the thesis, we study the boiler by itself and then match it with the solar collector as a consolidated system. The boiler is a water container full of brackish water. It has a helical coil, which the HTF passes through. This coil transfers the heat to the water to boil it. The pressure of the boiler container is lower than the atmospheric pressure. Thus, the saturation temperature is lower as the boiler pressure is lower. Hence, the system can evaporate and boil water at the lower working temperatures. We calculated the system properties at various pressures and based on them determine the other properties of the regime including the length of the coil in the boiler and solar collector.

For calculations in the boiler obviously the HTF mass flowrate in the coil should be equal the mass flowrate at the solar collector receiver.

Heat Transfer at Boiler:

In this section, we calculate the heat that the HTF losses in the boiler coil. While the HTF passes through the helical coil in the boiler, its temperature drops from inlet to exit. This temperature reduction causes this amount of the heat that the HTF transfers to the boiler. However, the inlet and outlet HTF temperatures at this stage are not determined. At the second step, we have to calculate the convection and conduction heat transfer to the outer coil wall surface. It is clear that by energy conservation law all the heat that HTF loss in steady state condition has to cross the coil and goes to the outer coil wall surface.

This transferred heat on the wall surface would cause the nucleate boiling and increasing the temperature of the inlet water to the water saturation temperature determined by the boiler pressure. The inlet water into the boiler is equal to the vaporized water in the boiler. Because the boiler pressure is kept constant, all the vaporized water is pumped out of the boiler.

Since we study our system under steady state conditions, we assume that the heat evaporating the brackish water will allow us to calculate the mass flowrate of the water vapor. In other words, the water vapor mass flowrate is equal to the heat transfer rate divided by the latent heat of vaporization ($\dot{m} = \frac{\dot{Q}}{h_{fg}}$). (We assume the water level of the boiler always remains constant.) Remember we assume the boiler walls are insulated well and there is no heat lost through the boiler walls to the environment. To solve these equations, we use the EES capability and its library to find the water properties as we did in the previous chapter for the air properties. The equations for calculating HTF properties in previous section are used as well.

Thermodynamic Heat:

The heat that the HTF loss when pas through the boiler coil can be find by:

$$Q_{fb} = \dot{m}\, C_{p,fb}(T_{fin} - T_{fout}) \qquad (22)$$

where $C_{P,fb}$ is heat capacity of HTF at the average HTF temperature at inlet and outlet of the boiler coil. T_{fin} and T_{fout} are Temperature at inlet and outlet of the coil respectively.

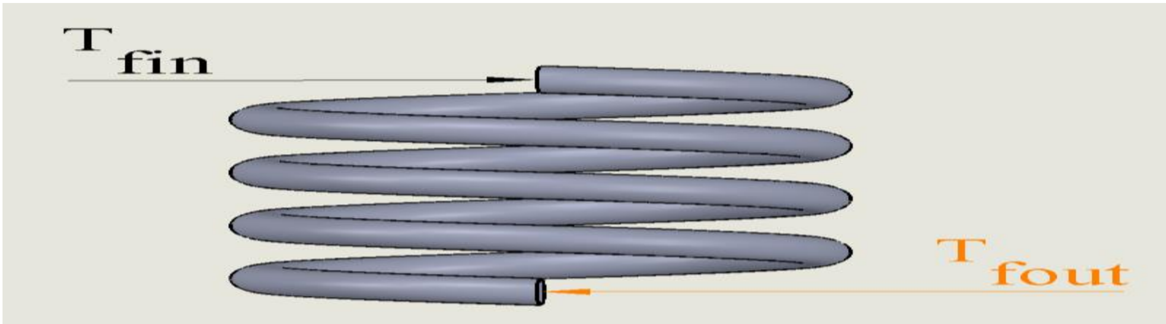

Figure 13. Boiler Helical coil, HTF enters to the coil at temperature T_{fin} and leaves the coil at temperature T_{fout}

Boiler Heat Transfer:

This heat is result of the convection and conduction heat transfer. The temperature of the outer surface of the helical coil is increased due to the heat that HTF give up by passing through the coil. Therefore, this temperature enhancement depends on the convection and conduction thermal resistance of the HTF and coil tube respectively.

To compute the heat transfer by convection and conduction to the outer surface of the coil wall use equation:

$$Q_{FSB} = \frac{T_{avgFB} - T_{cbs}}{R_{totalFSB}} \quad (23)$$

$$R_{totalFSB} = \frac{\ln(\frac{r_{2coil}}{r_{1coil}})}{2\ \Pi\ L_{coil}\ K_{coil}} + \frac{1}{2\Pi r_{1coil}\ L_{coil}\ h_{fb}} \quad (24)$$

T_{avgFB} : average HTF temperature between inlet and outlet of the coil
T_{cbs} : outer coil surface temperature
r_{1coil} : inner coil radius
r_{2coil} : outer coil radius
K_{coil} : copper heat conductivity
L_{coil} : coil length
h_{fb} : HTF convection heat transfer coefficient in the coil

Because the flow in the coil is turbulent, we can find the convection heat transfer coefficient for flow:

$$h_{fb} = \frac{NU_{Dfb}\ K_{fb}}{D_{1coil}} \quad (25)$$

$$NU_{Dfb} = .0265\ Re_{fb}^{\frac{4}{5}}\ Pr_{fb}^{0.3} \quad (26)$$

$$Re_{fb} = \frac{\dot{m}\, D_{1coil}}{A_{crossCoil}\, \mu_{fb}} \quad (27)$$

All properties of HTF should be evaluated at T_{avgFB}.

Boiling Heat Transfer:

We assume that the difference between the outer wall surface of the coil and the water temperature at saturation point under boiler pressure is more than 30ºC. Therefore, boiling occurs in a nucleate regime. To compute nucleate boiling heat per square meter we use Equation 28. The value of $C_{s,f}$ and n, which are dimensionless coefficient factor, from surface and fluid combination Table 4 correspond to 0.0128 and 1 respectively as we assuming that we use polished copper.

$$q_s = \mu_l\, h_{fg} \left[\frac{g\,(\rho_l - \rho_\vartheta)}{\sigma}\right]^{\frac{1}{2}} \left[\frac{C_{p,l}\, \Delta T_e}{C_{s,f}\, h_{fg}\, Pr_l^n}\right]^3 \quad (28)$$

To find the other properties we use the EES library for saturation temperature and water quality. For our system, the total nucleate boiling is

$$Q_{sreal} = A_{coil}\, q_s \quad (29)$$

Therefore, the amount of the mass rate can be found by:

$$\dot{m}_\vartheta = \frac{Q_{sreal}}{h_{fg}} \quad (30)$$

The total heat that transfer to the water from the coil is:

$$Q_{SB} = Q_{sreal} + \dot{m}_\vartheta\, C_P\, (T_{sat} - T_{Waterinlet}) \quad (31)$$

By first law of thermodynamic, all mentioned heat transfer rates are equal to each other. Therefore, we are capable to find all variables that we are interested in designing a device. Also for finding efficiency of the system, we use:

$$COP = \frac{\dot{m}_\vartheta\, h_{fg}}{Q_{Sun}} \quad (32)$$

Chapter 3: Results and Analysis:

There are some critical parameters in system design that affect other components parameters, and to determine them we need a thorough analysis our results. These parameters are the mass flowrate of the clean produced water ($\dot{m}_v$), solar collector length, required heat, and boiler coil length. For the purpose of the simple analysis, we assume that the water inlet temperature is assumed to be 40ºC.

Changing parameters along changing water vapor mass flowrate:

To see the effect of variation in parameter changes along with the changing water vapor mass flowrate we assume constant values of the other properties, and compare the results data due to that assumption.

Figure 14 shows the required heat to produce a water vapor mass flowrate when the boiler pressure is constant (0.1[atm]), and the HTF mass flowrate is $0.05\ [\frac{\text{kg}}{\text{s}}]$. Therefore, the solar collector length will vary depending on the system output when we preserve these conditions. This length change is shown in Figure 15.

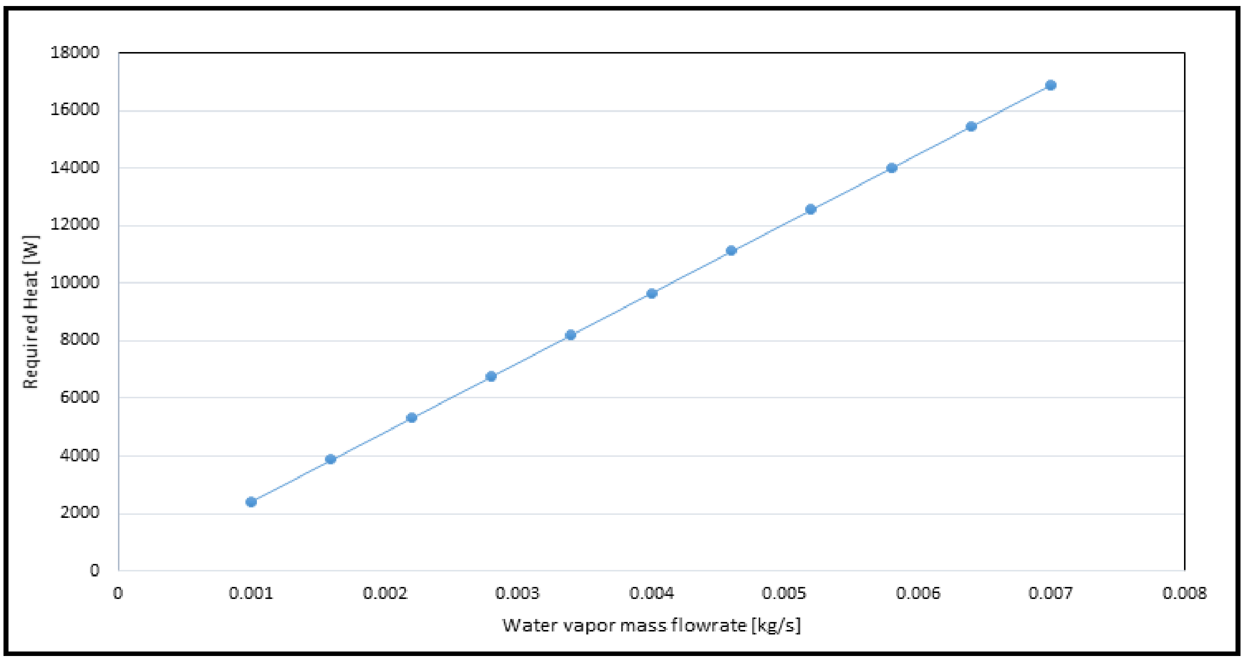

Figure 14. Required heat for producing clean water when the boiler pressure at 0.1 [atm], the inlet brackish water temperature at 40ºC, and HTF mass flowrate at 0.05 kg/s remain constant.

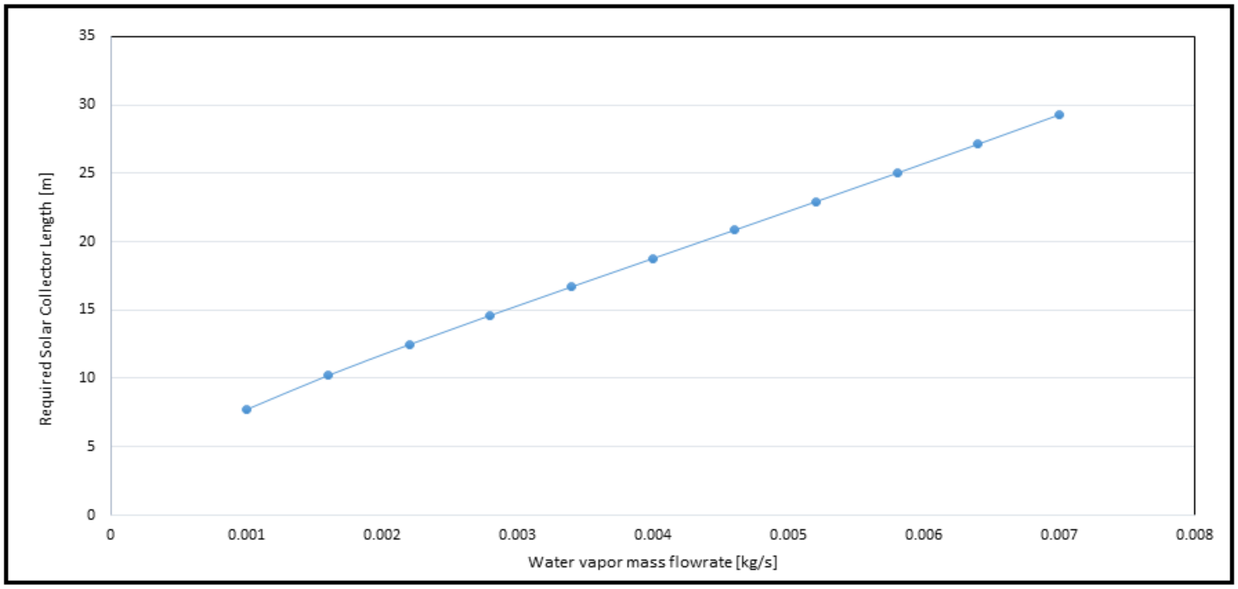

Figure 15. Required solar collector length for producing clean water when the boiler pressure at 0.1 [atm], the inlet brackish water temperature at 40 ºC, and HTF mass flowrate at 0.05 [kg/s] remain constant.

Remember that for water, $1\ \frac{kg}{s} \cong 3600\ \frac{lit}{hr}$

Because the boiler pressure is kept constant, the saturation temperature remains constant too. As is shown in Figure 14 the required heat, which is absorbed by the HTF, has a linear relation to the mass flowrate of produced clean water. Therefore, as the length of the solar collector decreases the temperature of the HTF decreases. Consequently, the temperature difference between the water saturated temperature and HTF temperature decreases. Hence, to transfer all the absorbed heat to the boiler water, it is required to have longer boiler coil. If this difference amount drops to a certain degree, we no longer have a nucleate boiling and it would enter to the natural convection heat transfer. The Figure 16 shows the relation between the produced fresh water mass flowrate vs. the boiler coil length. Note that the boiler coil length variation also encompasses different temperature differences. It is demonstrated that as the amount of the absorbed heat reduced the duration of the boiler coil had to increase. Also, it shows how much the required boiler coil length increases if we enter to the natural convection region to transfer all the absorbed heat to the water.

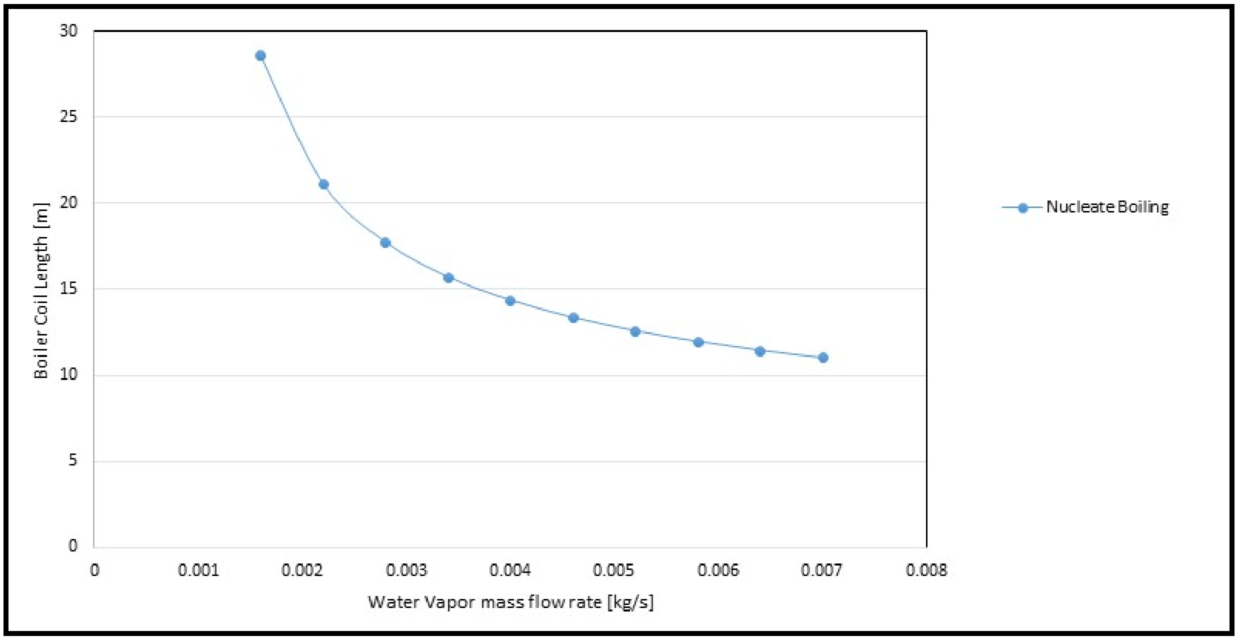

Figure 16. Required boiler coil length for producing for producing clean water when the boiler pressure at 0.1 [atm], the inlet brackish water temperature at 40 ºC, and HTF mass flowrate at 0.05 [kg/s] remain constant

The Figure 17 shows how the system efficiency effects by clean water produced while the boiler pressure is constant (0.1 [atm]) and inlet brackish water to the boiler is 40 C. The HTF mass flowrate is constant (0.05 [kg/s]). It illustrates that the efficiency of the system increases while the length of the solar collector increases and consequently HTF temperature increases. As the HTF temperature enhances the heat loss, increases too. As efficiency exceeds 55%, the slope of the graph decreases that means the rate of increasing the efficiency depending on the increasing length is not as big as below this amount. In other words, to improve the effectiveness of the system by 1% it is required much more length to the solar collector than before we over COP 55%.

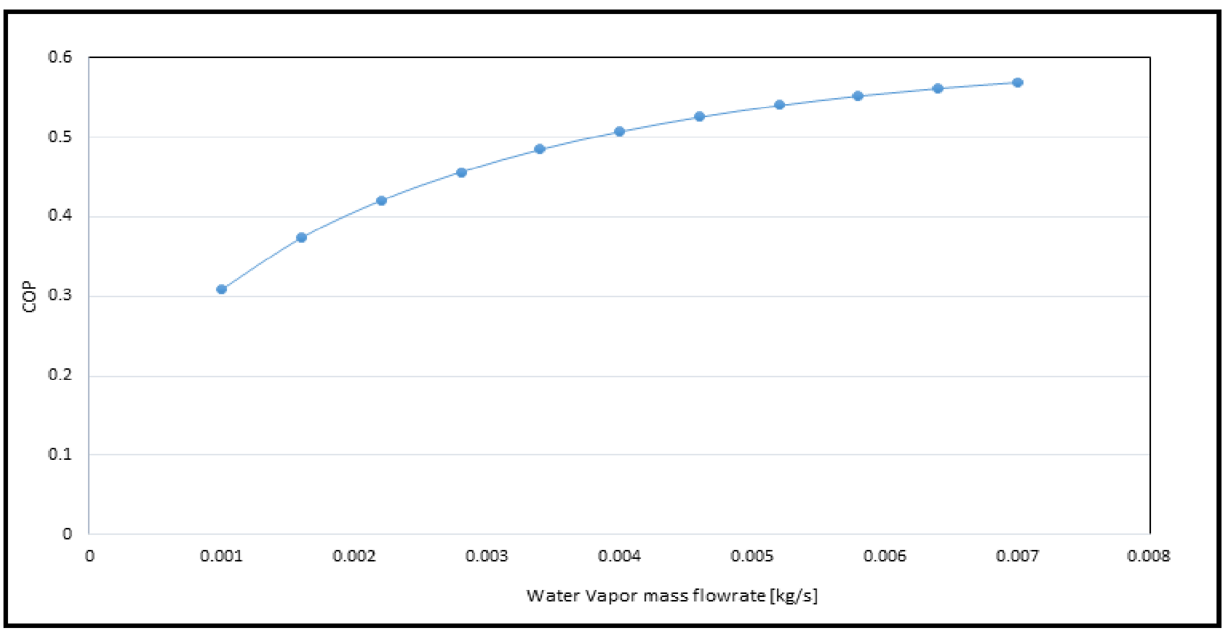

Figure 17. System Efficiency vs. producing clean water when the boiler pressure at 0.1 [atm], the inlet brackish water temperature at 40 ºC, and HTF mass flowrate at 0.05 [kg/s] remain constant.

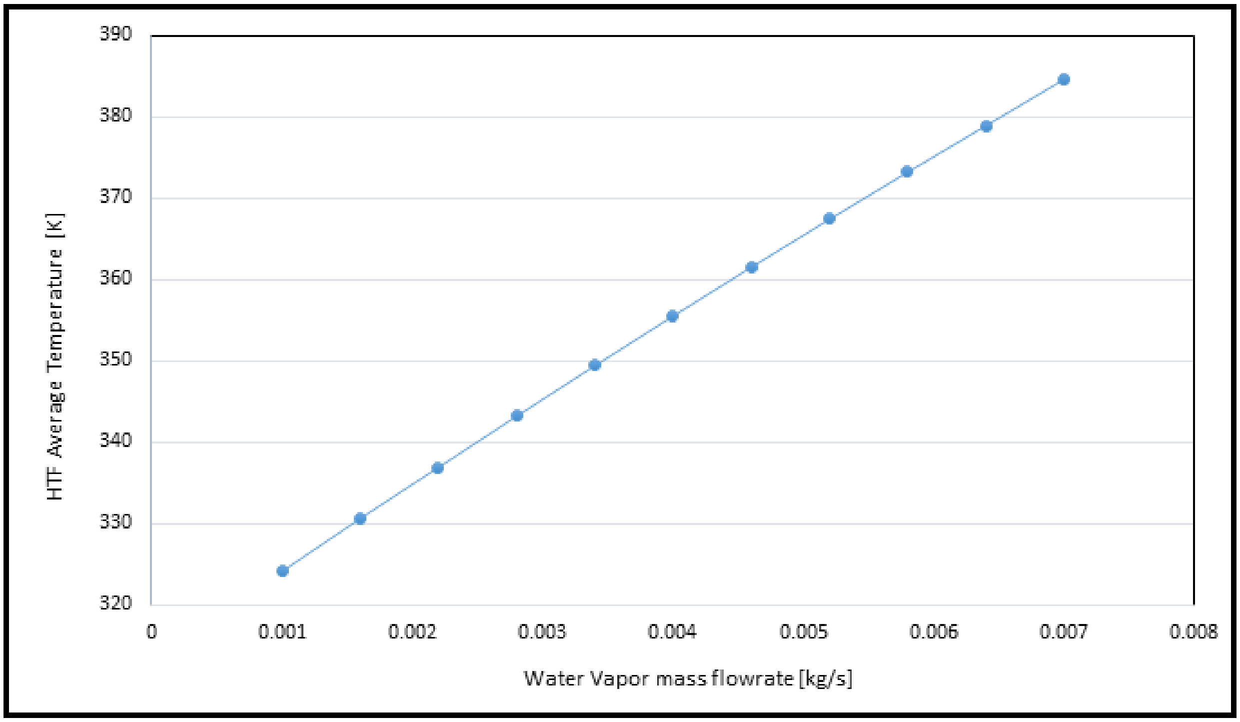

Figure 18. HTF Average temperature vs. producing clean water when the boiler pressure at 0.1 [atm], the inlet brackish water temperature at 40 ºC, and HTF mass flowrate at 0.05 [kg/s] remain constant.

These results extracted for HTF mass flowrate 0.05 [kg/s], which consider the laminar flow at the solar collector pipe. Later we will explain the results for both laminar and turbulent flow and will compare them together when the HTF mass flowrate is variable.

Table 1 shows how the parameters changes while the mass flowrate of produced water changes.

Table 1. Parameters changes depend on the clean water mass flowrate when the boiler pressure kept constant at 0.1 [atm] and HTF mass flowrate at 0.05 [kg/s] remains unchanged

$\dot{m}_V[\frac{kg}{s}]$	$\dot{m}_V[\frac{lit}{s}]$	**Q** [W]	**Solar collector length** [m]	**Boiler coil length** [m]	**HTF avg Temp. in solar collector** [K]	**Solar Collector Surface Temp.** [K]	**COP**
0.007	25.2	16921	29.31	10.99	384.6	511	0.5692
0.0064	23.04	15471	27.16	11.42	378.9	513.2	0.5617
0.0058	20.88	14021	25.03	11.94	373.2	516	0.5522
0.0052	18.72	12570	22.94	12.56	367.4	519.4	0.5403
0.0046	16.56	11120	20.86	13.34	361.5	523.5	0.5255
0.004	14.4	9669	18.79	14.34	355.5	528.6	0.5073
0.0034	12.24	8219	16.72	15.7	349.4	534.7	0.4846
0.0028	10.08	6769	14.63	17.71	343.2	542	0.4562
0.0022	7.92	5318	12.48	21.11	336.9	550.9	0.4202
0.0016	5.76	3868	10.22	28.55	330.6	561.9	0.3732
0.001	3.6	2417	7.73	63.59	324.1	576	0.3083

Changing Parameters along with Changing Boiler Pressure:

Constant water vapor:

If boiler pressure varies, it will affect other parameters. To achieve the proper result, we specify two other parameters. First it is assumed that the amount of the produced clean water is constant for example 0.004336 [kg/s] which is approximately 15.6 [lit/hr], and HTF mass flowrate 0.05 [kg/s]. This amount of the HTF mass flowrate generates laminar flow at the solar collector. Different boiler pressures require different solar lengths in respect to the boiler pressure. Since the water saturation temperature depends on the boiler pressure, the system needs more heat while the saturation temperature increases. Therefore, the length of the solar collector increases to absorb more heat as the boiler pressure increases. However, to achieve the highest efficiency and reduce manufacturing cost it is necessary to reduce the boiler pressure because the higher boiler pressure will cause the longer boiler coil length and longer solar collector length. Figures 19 and 20 show how solar collector length and system efficiency change by boiler pressure.

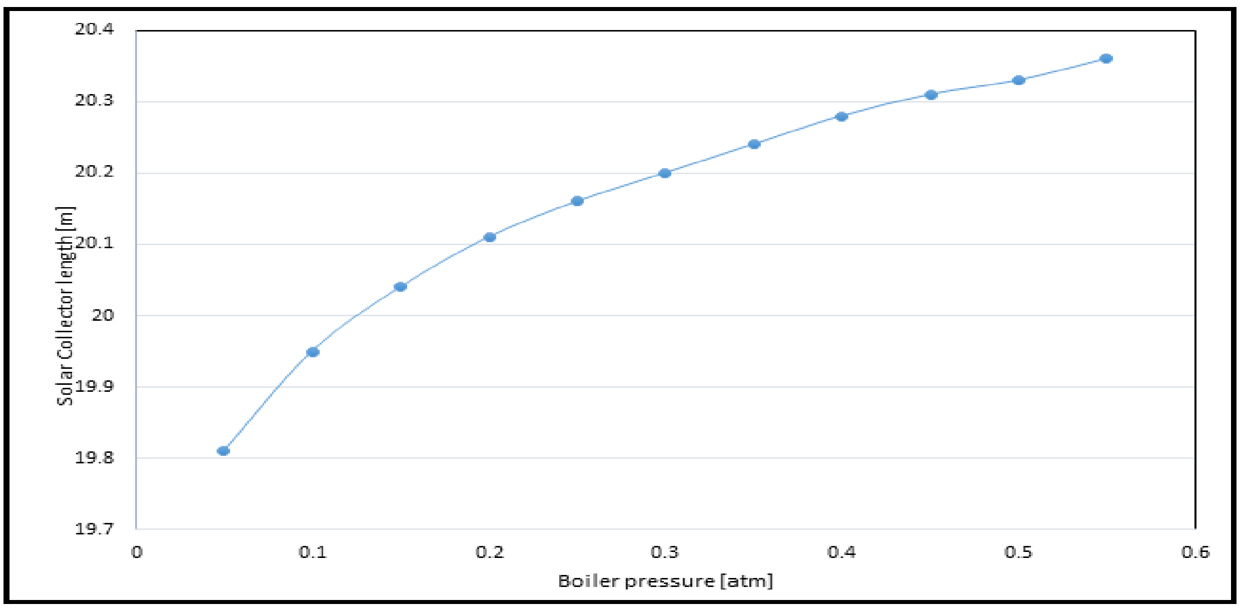

Figure 19. Solar collector length vs. Boiler pressure while the produced clean water is constant at 15.6 [lit/hr] (0.004336 [kg/s]). The inlet brackish water temperature at 40 ºC, and HTF mass flowrate at 0.05 [kg/s] remain constant.

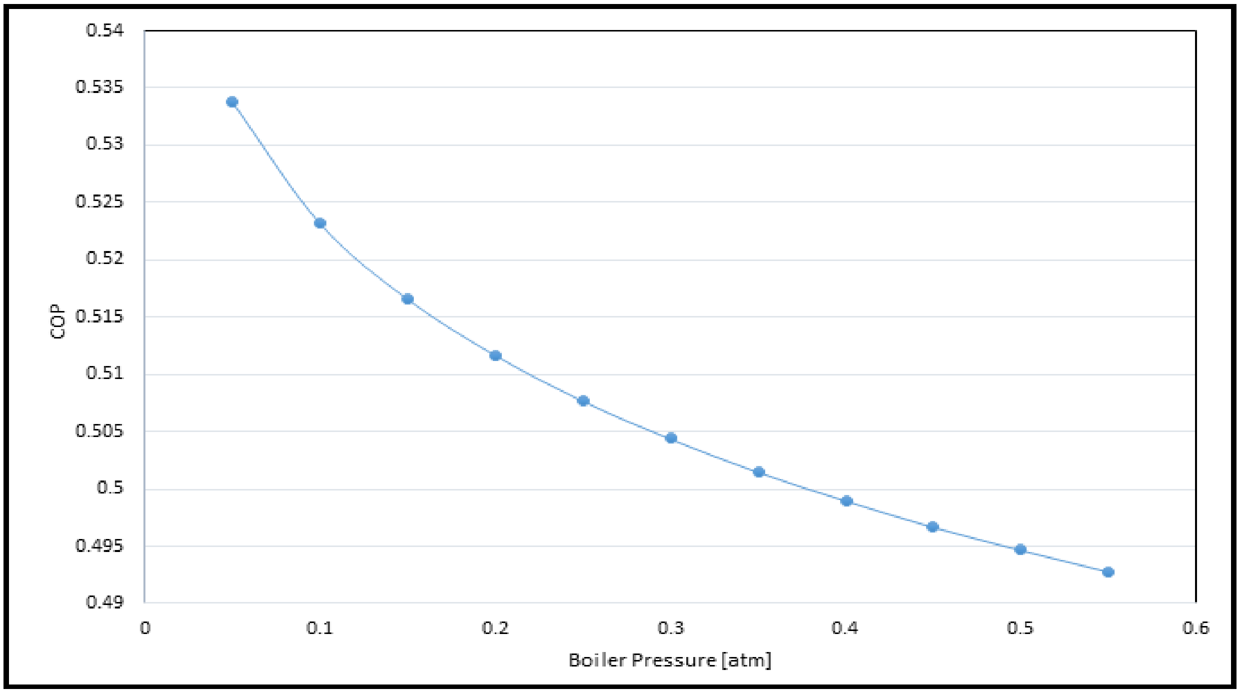

Figure 20. Efficiency vs. Boiler pressure while the produced clean water is constant at 15.6 [lit/hr] (0.004336 [kg/s]). The inlet brackish water temperature at 40 ºC, and HTF mass flowrate at 0.05 [kg/s] remain constant.

Table 3 shows how the parameters changed when the boiler pressure changes while the clean water is produced is kept constant (0.004336 [kg/s]).

Table 2 Changing parameters along boiler pressure changes with constant produced clean water mass flowrate at 0.004336 [kg/s]

P [atm]	Solar Collector Length [m]	Absorbed Heat [W]	HTF Average Temp. [K]	Boiler coil Surface Temp. [K]	Solar collector Surface Temp. [K]	Water Saturation Temp. [K]	Boiler coil Length [m]	COP
0.05	19.81	10381	358.4	313.8	526	306.3	9.909	0.5338
0.1	19.95	10482	358.8	326.5	525.7	319.2	13.74	0.5232
0.15	20.04	10544	359.1	334.3	525.4	327.4	17.99	0.5166
0.2	20.11	10591	359.3	340	525.3	333.5	23.18	0.5117
0.25	20.16	10628	359.4	344.1	525.2	338.4	29.26	0.5077
0.3	20.2	10659	359.6	347.5	525	342.6	37.4	0.5044
0.35	20.24	10685	359.7	350.5	525	346.2	49.18	0.5015
0.4	20.28	10709	359.8	353.1	524.9	349.3	67.83	0.499
0.45	20.31	10729	359.9	355.4	524.8	352.2	101.5	0.4967
0.5	20.33	10748	359.9	357.4	524.8	354.8	178.2	0.4947
0.55	20.36	10765	360	359	524.7	357.2	468.6	0.4928

Constant solar collector length:

If both the solar collector length and the amount of the produced clean water is kept constant, then the system required heat changes via the boiler pressure. Now as we decrease the boiler pressure the saturation temperate for water decreases too. Therefore, a lower temperature is required for vaporizing the brackish water in the boiler. Thus, if the solar collector length remains constant while the boiler pressure decreases, because HTF absorbs a constant heat at this collector length, the water vapor mass flowrate increases due to greater temperature difference and increased heat transfer in the boiler.

As an example, we chose 17 [m] as the solar collector length, with HTF mass flowrate 0.05 [kg/s]. Therefore, the data is obtained when the flow in the solar collector is laminar. The water inlet to the system is 40ºC. The quantities via boiler pressure changes are acquired and shown in Figures 21 and 22.

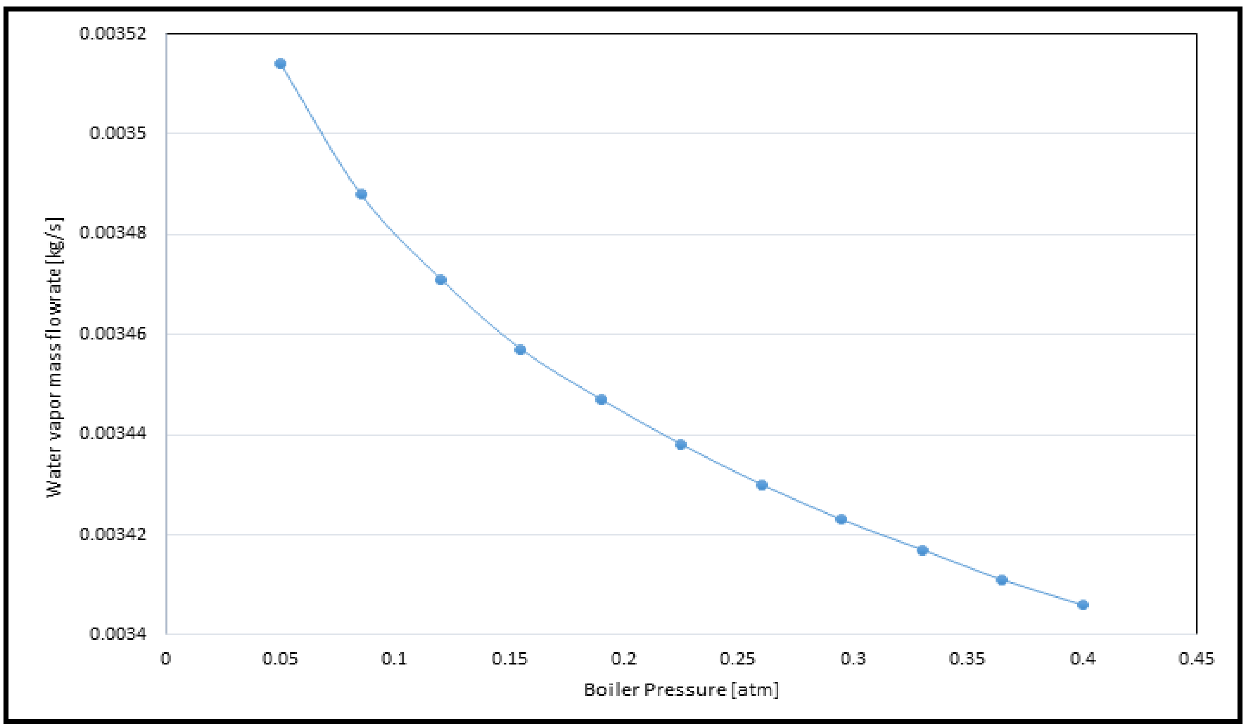

Figure 21. Boiler Pressure vs. Mass flowrate of the produced clean water when the solar length is constant at 17[m]. The inlet brackish water temperature at 40 ºC, and HTF mass flowrate at 0.05 [kg/s] remain constant.

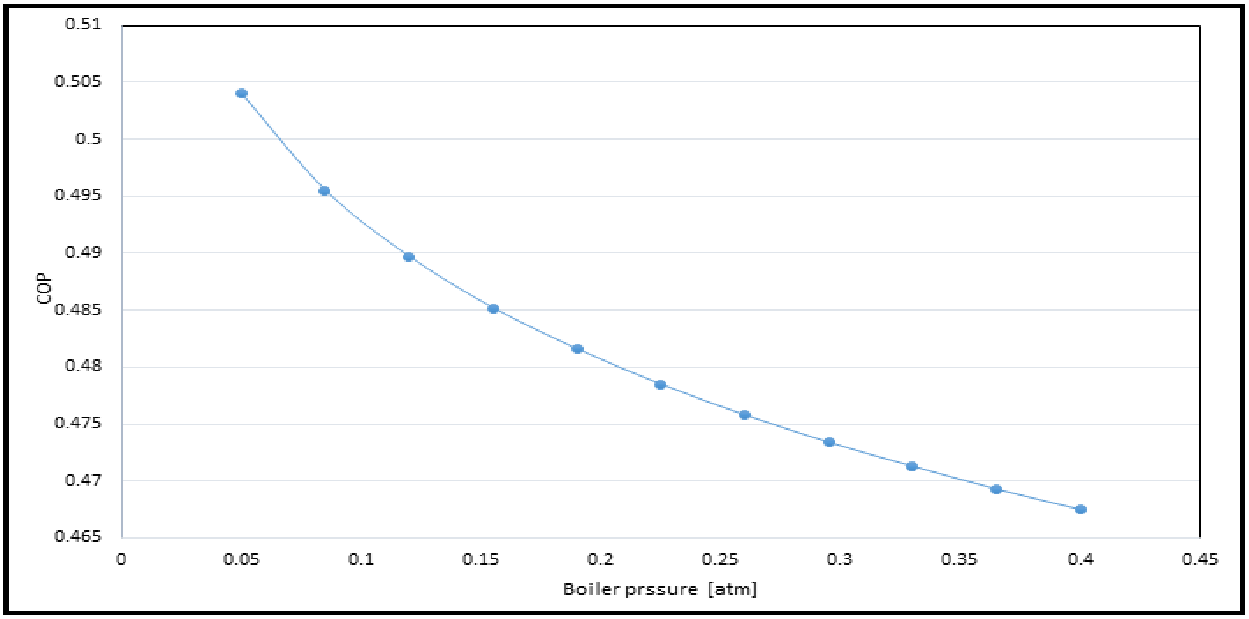

Figure 22. Boiler Pressure vs. efficiency when the solar length is constant at 17[m]. The inlet brackish water temperature at 40 ºC, and HTF mass flowrate at 0.05 [kg/s] remain constant.

Table 3 shows how the parameters changed along boiler pressure changing while solar collector length kept constant at 17 [m], the HTF mass flowrate is 0.05 [kg/s], which cause the laminar flow at the solar collector, and the water inlet to the boiler is 40 ºC.

Table 3 Changing parameters along boiler pressure while the solar collector length is constant at 17 [m] long

P	$\dot{m}_V$ [$\frac{kg}{s}$]	$\dot{m}_V$ [$\frac{lit}{hr}$]	***Solar Collector Surface Temp.*** *[K}*	***Saturation Temp.*** *[K]*	***Boiler Coil Length*** *[m]*	***COP***
0.05	0.003514	12.6504	533.8	306.3	10.27	0.504
0.085	0.003488	12.5568	533.8	316.1	13.81	0.4955
0.12	0.003471	12.4956	533.8	322.8	17.99	0.4897
0.155	0.003457	12.4452	533.8	328.1	23.34	0.4852
0.19	0.003447	12.4092	533.8	332.4	30.66	0.4816
0.225	0.003438	12.3768	533.8	336.1	40.84	0.4785
0.26	0.00343	12.348	533.8	339.3	56.35	0.4758
0.295	0.003423	12.3228	533.8	342.2	84.17	0.4734
0.33	0.003417	12.3012	533.8	344.8	146.4	0.4713
0.365	0.003411	12.2796	533.8	347.2	369.4	0.4693
0.4	0.003406	12.2616	533.8	349.3	5663	0.4675

Changing Parameters along with HTF mass flowrate in laminar and turbulent region:

Now we study the system when HTF mass flowrate changes under two different conditions. This section illustrates the obtained properties along with changing the HTF mass flowrate. Because the HTF flowrate varies in this analysis, we consider both laminar flow and turbulent flow in the solar collector. Therefore, readers can compare system properties in the laminar region and the turbulent region.

In the first condition the solar collector length is held constant, and in the second condition the water vapor mass flow rate, $\dot{m}_V$, is held constant. Comparison of these two conditions results gives designers a good sense to justify their design between cost and system efficiency. In following in brief, we explain the results for each condition.

In the first condition let's assume the solar collector length is constant 18.8 [m]. Later we will explain why this length is a reasonable length when the flow in the solar collector is laminar. In this case the boiler pressure is constant at 0.1 [atm]. Because the solar length is constant as we increase the HTF mass flowrate, the rate of the absorbed heat increases too. Consequently, the amount of the $\dot{m}_V$ increases as well. When the flow is turbulent the heat transfer rate will increase remarkably. Although the sensitivity of the heat absorbed to the HTF mass flow rate is lower in the turbulent region and increasing the mass flow rate does not have as large an effect. In other words, the slope of the $\dot{Q} - \dot{m}$ curve is smaller in the turbulent region than laminar region. Because the heat transfer rate increases in turbulent flow, the mass flowrate of the water vapor notably increases too. When the HTF mass flowrate goes over 0.1766 kg/s the Reynolds number for the flow in the solar collector is more than 2500. Thus, we pass the laminar region and enter to the turbulent region at this point. However, at the number around this point the transition flow exists. To avoid complexity and make the result more predictable we use the turbulent correlation. In the second condition, the amount of the produced water mass flowrate is constant 0.004336 [kg/s] (15.6 [lit/hr]). When $\dot{m}_V$ is constant, the system requires a constant heat for a constant output. Therefore, by increasing the HTF mass flowrate, the length of the solar collector decreases because the system is able to absorb the same amount of heat with shorter length. When the flow in the solar collector is turbulent, HTF is able to absorb even a lot more heat. Therefore, the required solar collector length is a lot shorter than the laminar flow.

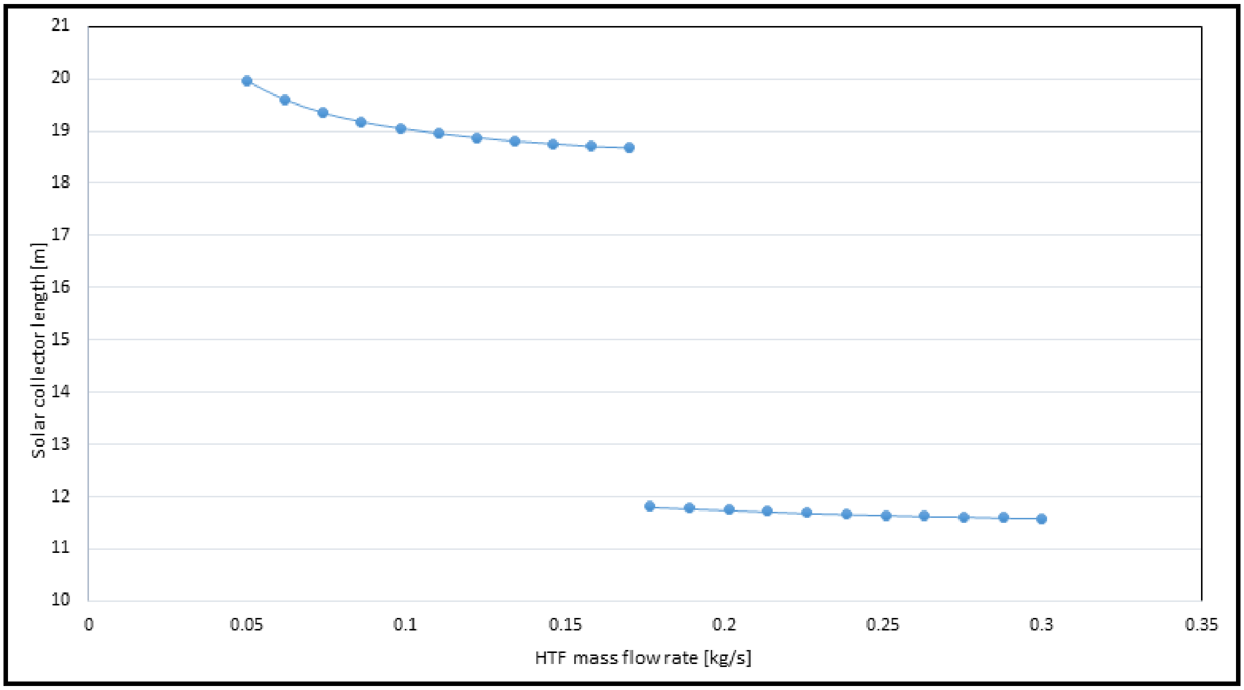

Figure 23. Required Solar collector length when $\dot{m}$ changes, for $\dot{m}_V$ is constant (0.004336 [kg/s]) and boiler pressure is constant (at 0.1 [atm]). When the HTF mass flowrate pass the .1766 [kg/s] the flow changed from laminar to turbulent flow.

Because ratio changes for the solar length to the HTF mass flowrate below 18.8 [m] is small, we picked this length as a reference length for the solar collector length to study parameter changes.

Figure 24 shows how the absorbed heat changes with the HTF mass flowrate in two different cases, Constant Solar collector length (18.8 [m]), and Constant $\dot{m}_V$. It also shows how turbulent flow changes the amount absorbed heat.

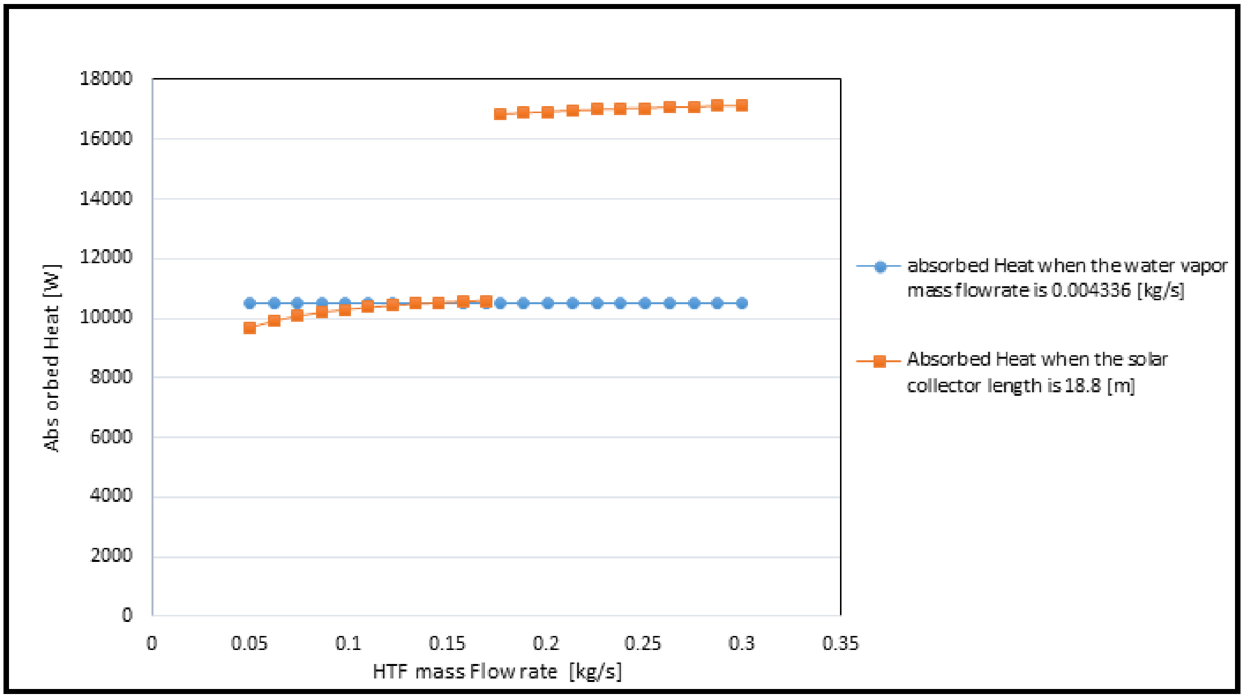

Figure 24. Shows how the absorbed heat changes along the HTF mass flowrate in two conditions. When the solar collector length is 18.8 [m] constant (Red), and when the output water mass flowrate is 0.0043336 [kg/s] (Blue). Boiler pressure is constant at 0.1 [atm]

By increasing the HTF flowrate, the level of the produced water increases when the solar collector length is constant. However, the size of the absorbed heat in turbulent regime is significantly higher. Therefore, pure water production enhances largely when the turbulent flow occurs in compare with laminar flow in the solar collector. Figure 25 shows the produced water flowrate changes along the HTF mass flowrate changes and compares the water vapor mass flowrate in turbulent and laminar flow at the solar collector when the boiler pressure 0.1 [atm].

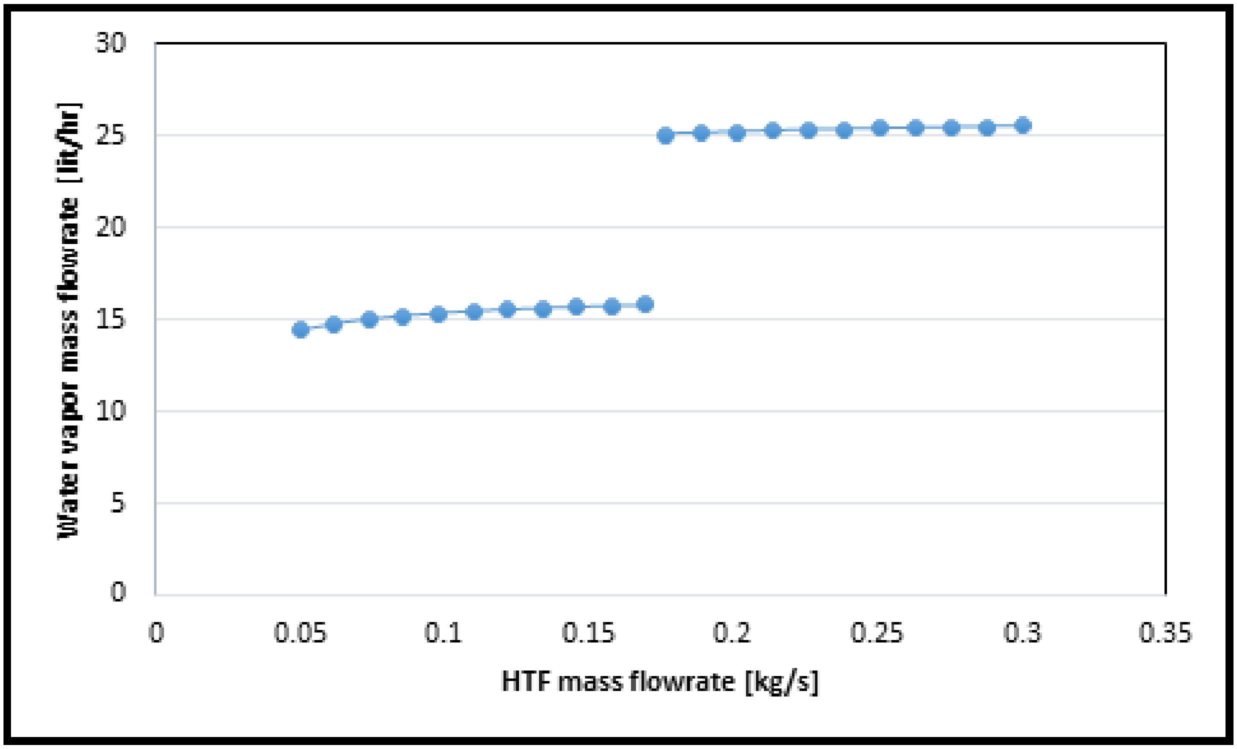

Figure 25. Compare changes of produced water to HTF mass flowrate when the solar collector length is 18.8 [m] and the boiler pressure is on the 0.1 [atm]

As the HTF flowrate increase, the surface temperature decreases because more heat can be removed from solar collector receiver pipe. Our results demonstrate that if the system is supposed to provide more water with the same HTF flowrate at constant pressure it has to have a longer solar collector to absorb more heat. Therefore, the average temperature of the HTF is higher. In contrast, the surface temperature of the solar collector receiver is lower (Figure 26). Because in turbulent regime there is more mixing to absorb heat from the solar collector receiver and a system with the longer receiver has a higher average HTF, and in contrast, the surface temperature of the receiver is lower.

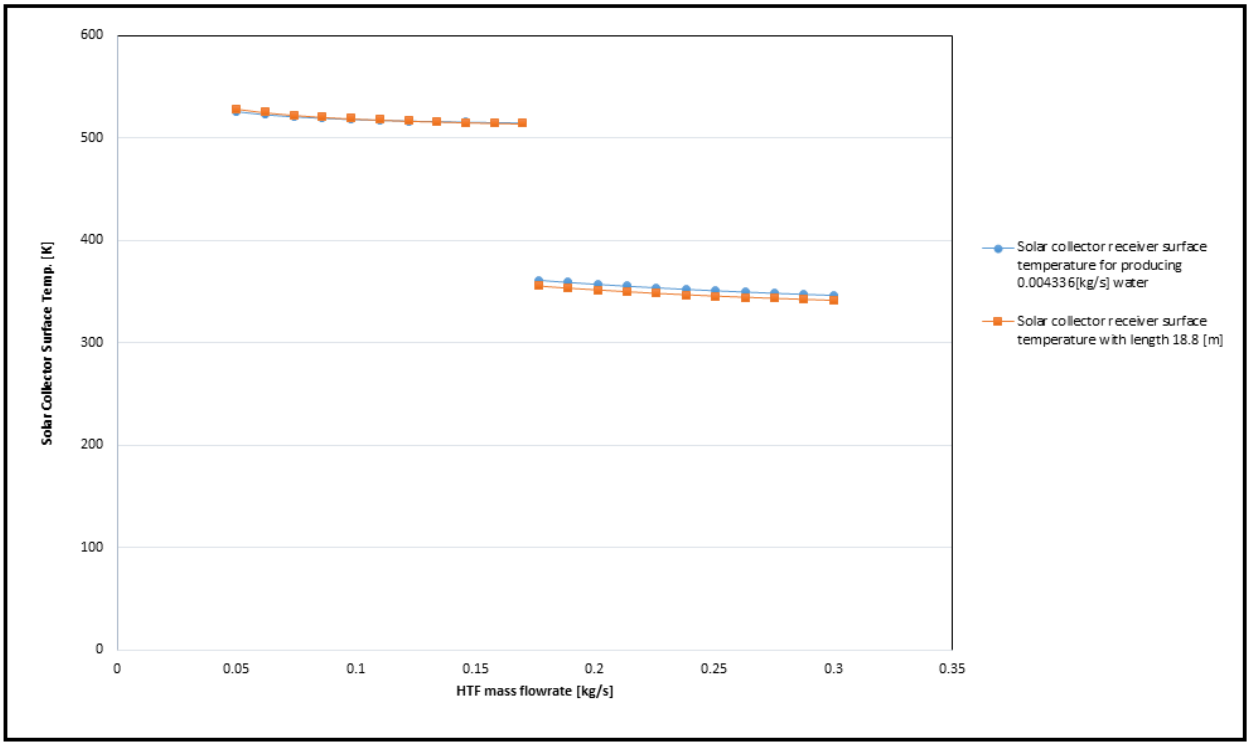

Figure 26. Solar collector receiver pipe surface temperature vs. HTF mass flowrate for two cases (the water mass flowrate 0.004336 [kg/s], and solar collector length is 18.8 [m]) when the boiler pressure is 0.1 [atm]

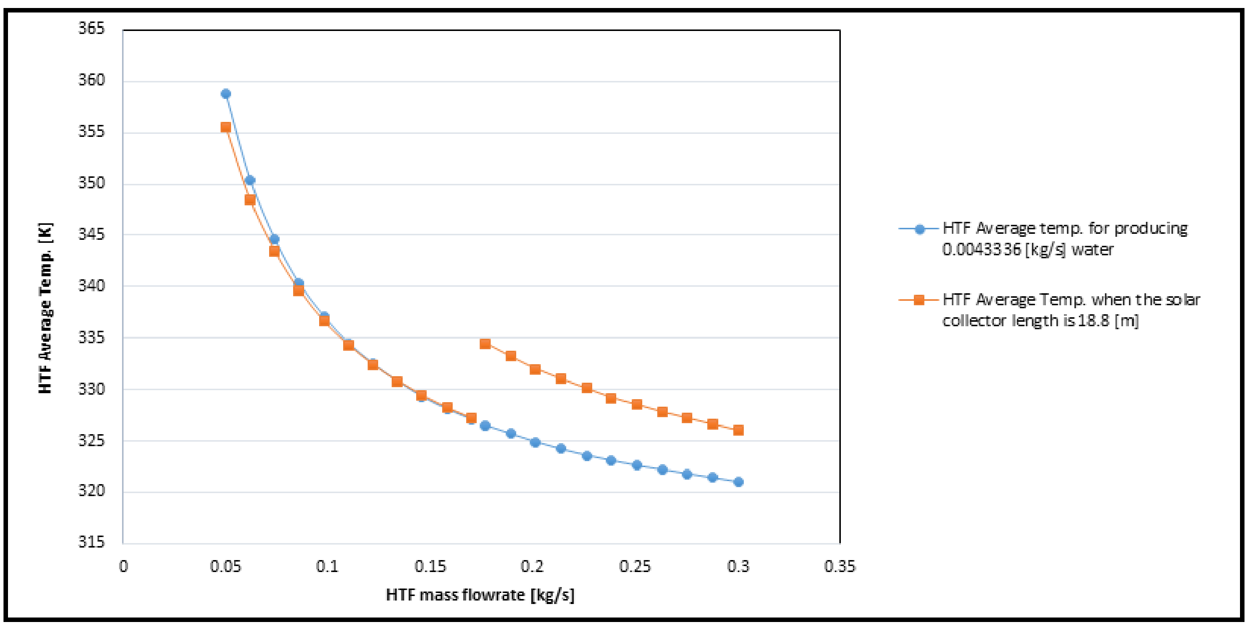

Figure 27. Solar collector receiver pipe surface temperature vs. HTF mass flowrate for two cases (the water mass flowrate 0.004336 [kg/s], and solar collector length is 18.8 [m]) when the boiler pressure is 0.1 [atm]

As the same manner, the boiler coil length increases while the HTF mass flowrate increases. The required boiler coil decreases when the system passed the laminar region and entered the turbulent region.

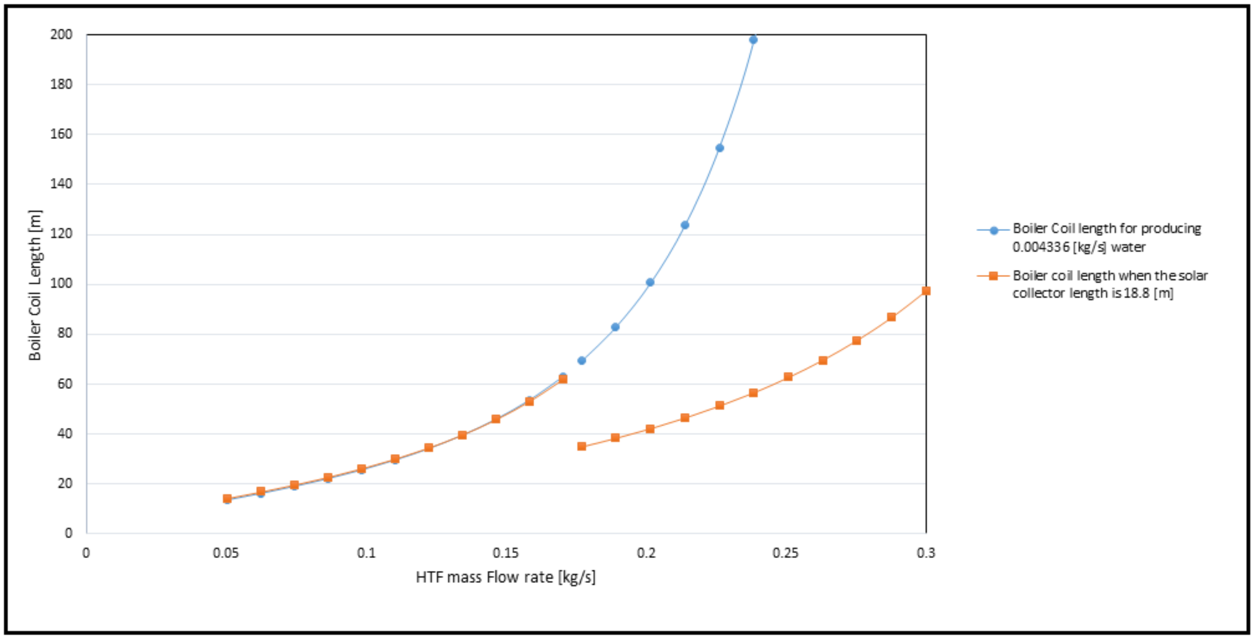

Figure 28. Boiler Coil Length changes compare to HTF mass flowrate for two cases (the water mass flowrate 0.004336 [kg/s], and solar collector length is 18.8 [m]) when the boiler pressure is 0.1 [atm]

Efficiency:

System efficiency has a direct relation to the HTF mass flowrate. As the HTF mass flowrate increases, the COP of the system increases too. The efficiency depends on the solar collector length. In another word, by adding to the solar collector length, the COP of the system enhanced too. However, this efficiency grows until it reaches the maximum point, which we call it maximum length point for that particular HTF mass flowrate, and after that point, the efficiency starts decreasing. Since it has a direct dependency to the HTF mass flowrate, as the mass flowrate increases, not only does the efficiency enhances, but also the value of the maximum length point grows too. However, this maximum length increased until the nature of the flow changed. When the flow type changed from laminar to turbulent flow in the solar collector the maximum length significantly decreased simultaneously, and after that started to grow slowly again. Efficiency also depends on the type of the flow in the solar collector. It means the turbulent flow in the receiver pipe has the higher efficiency than laminar flow. Figure 28 compares the COP of the system to the HTF mass flowrate for two cases (when the produced water mass flowrate is constant (0.004336 [kg/s]) and when the solar collector length remains constant at 18.8 [m]) the boiler pressure is 0.1 [atm] in both flow types (laminar and turbulent). In this section, we neglect the pump work in computing system efficiency because for circulation pump it is too small in comparison with the incoming energy through the sun, and for the vacuum pump, it is one-time use.

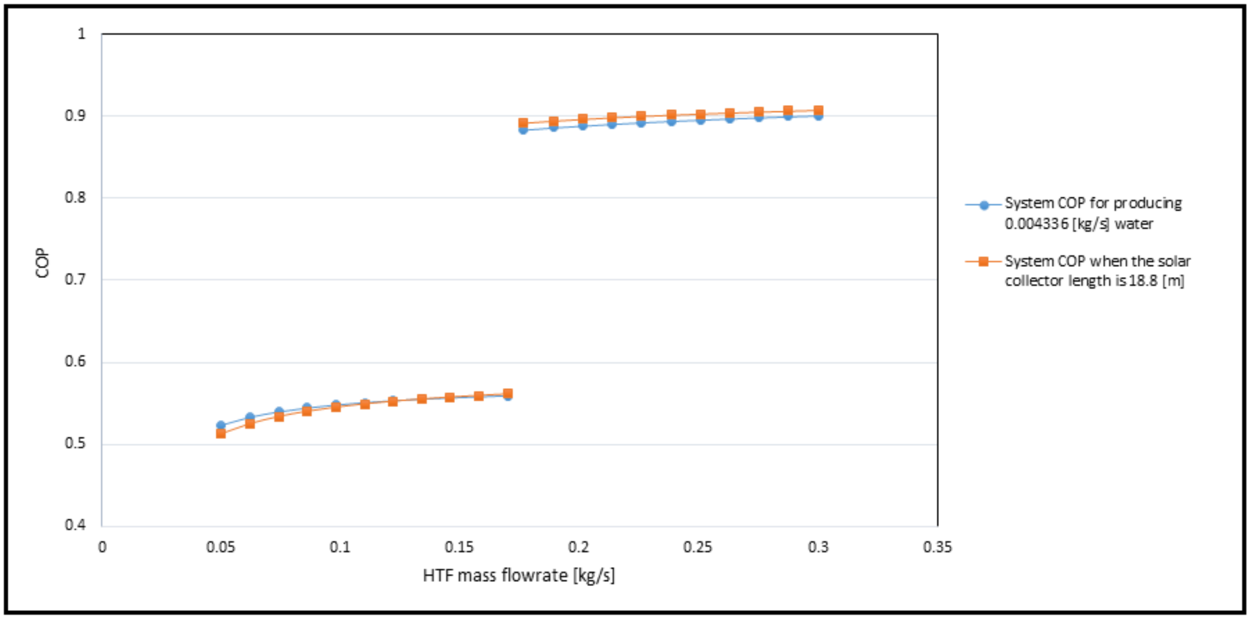

Figure 29. Compare the COP of the system to the HTF mass flowrate for two cases (when the produced water mass flowrate is constant (0.004336 [kg/s]) and when the solar collector length remains constant at 18.8 [m]) the boiler pressure is 0.1 [atm] in both flow type (laminar and turbulent).

Figures 30 to 32 show how the efficiency increases by increasing the length to reach the maximum length in different HTF mass flowrates, and after that it starts to decrease as the length increases. Figures 30 and 31 show the curve of the COP vs. solar collector length when the flow is laminar and Figure 32 when the flow is turbulent. As it is illustrated, the maximum length occurs at around 42 [m] when the HTF mass flowrate is 0.05 [kg/s] while the HTF mass flowrate is 0.15 the maximum length is about 71 [m]. However, the maximum length is 20 [m] when the HTF mass flowrate is 0.2 [kg/s] because the type of the flow changed from the laminar to the turbulent. Figure 31 compares three different flowrates for the COP calculation.

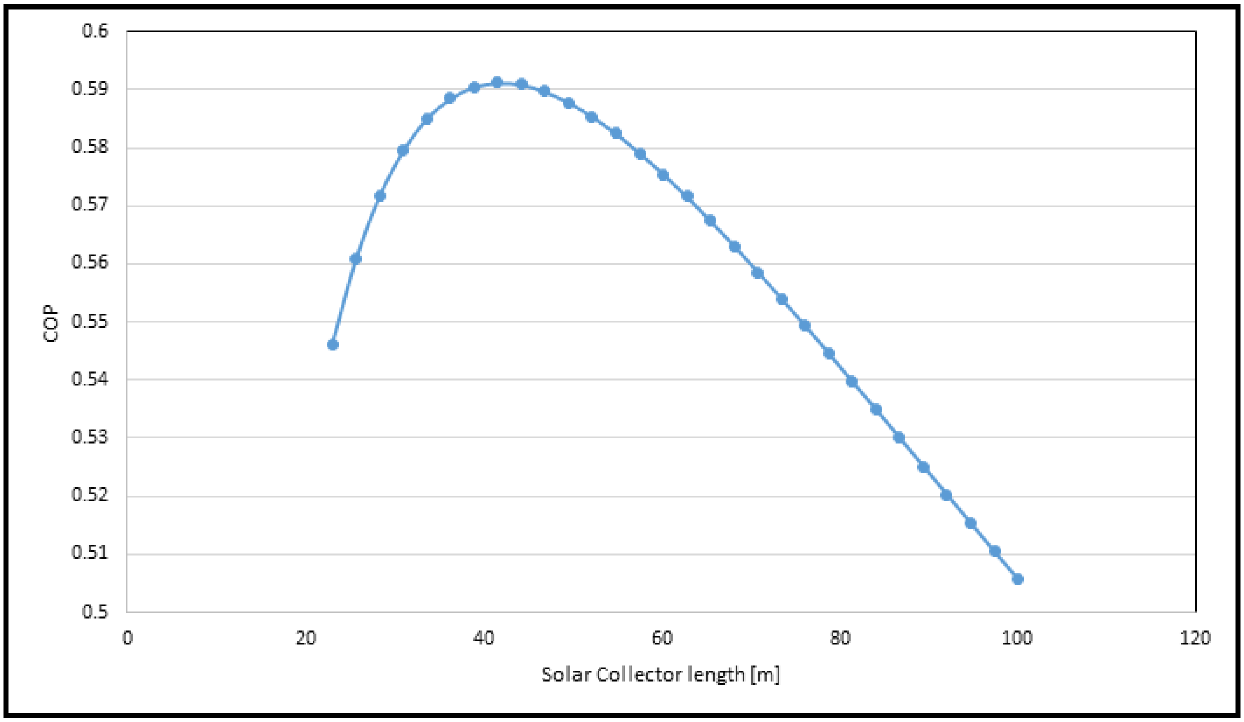

Figure 30. Compare system efficiency with solar length at boiler pressure 0.1 [atm] when HTF mass flowrate is 0.05 [kg/s]

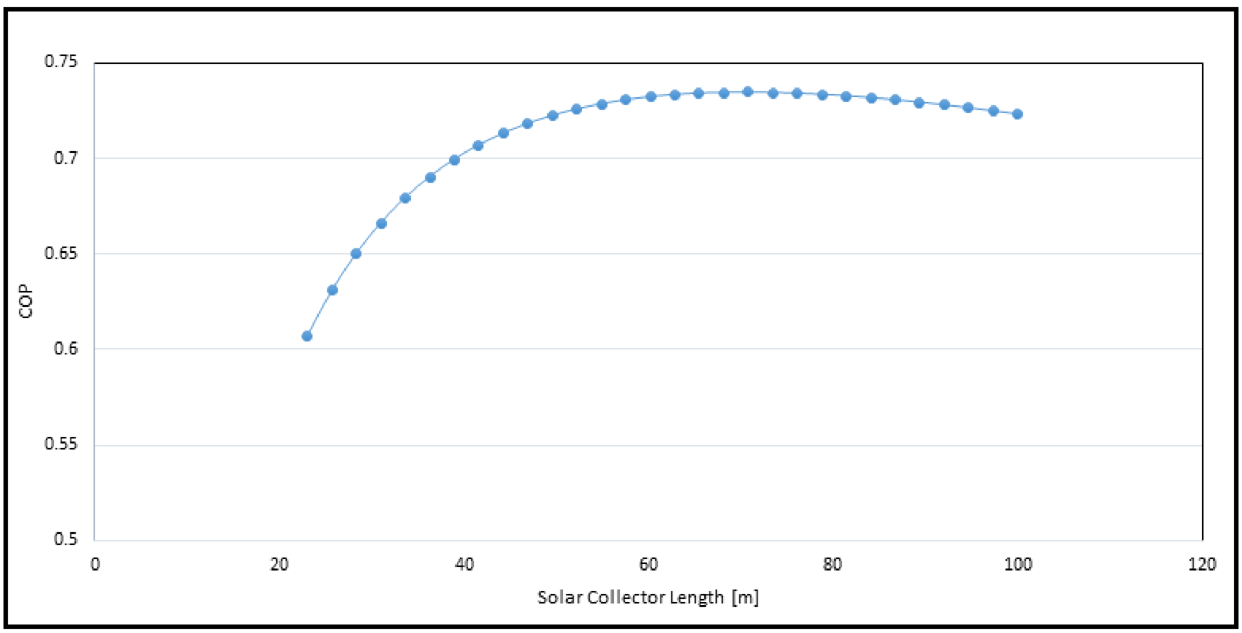

Figure 31. Compare system efficiency with solar length at boiler pressure 0.1 [atm] when HTF mass flowrate is 0.15 [kg/s]

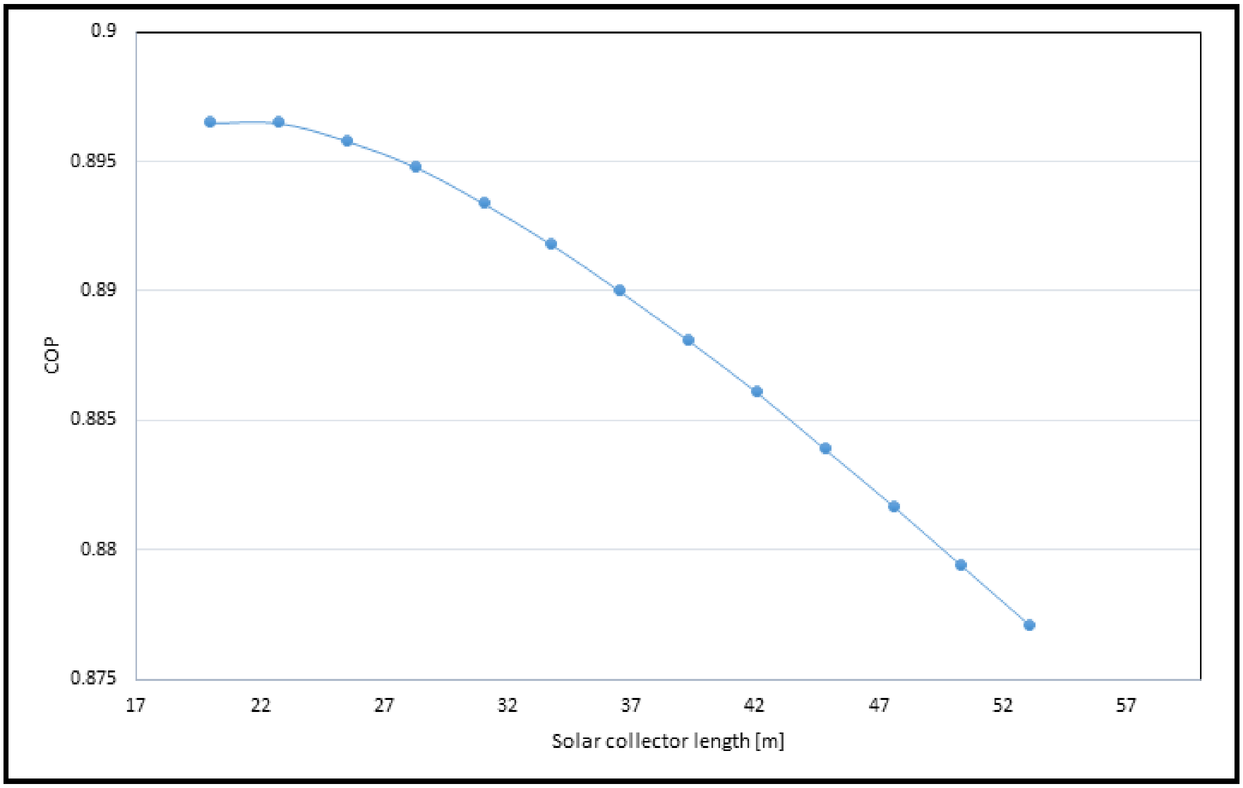

Figure 32. Compare system efficiency with solar length at boiler pressure 0.1 [atm] when HTF mass flowrate is 0.2[kg/s]

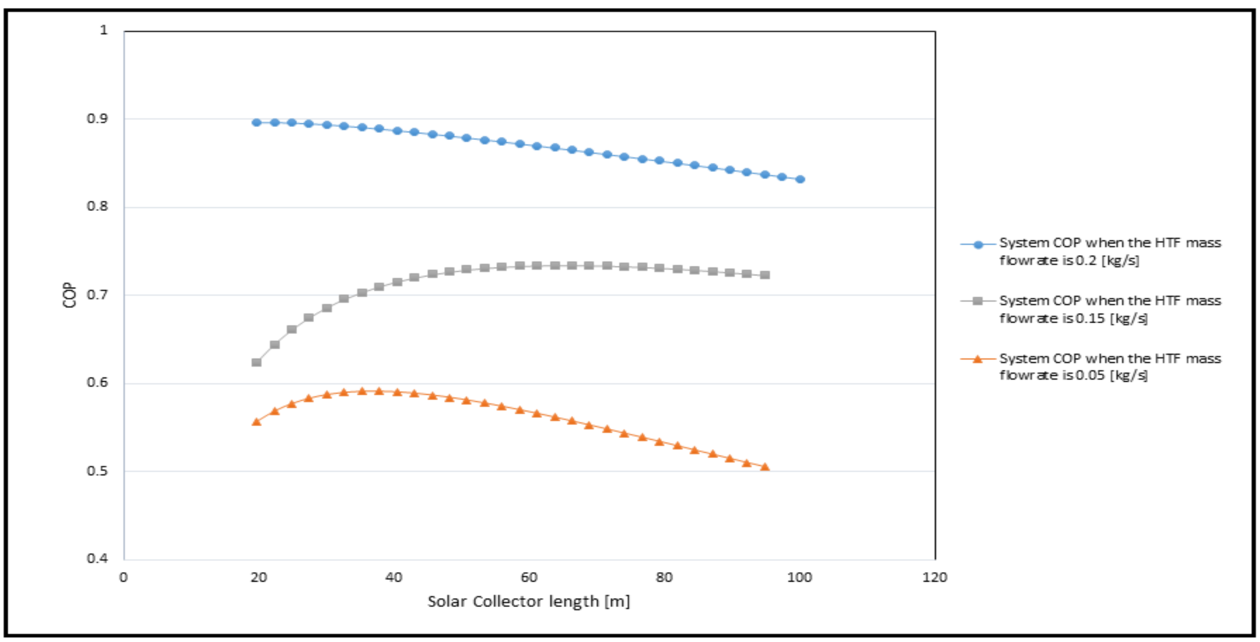

Figure 33. Compare system efficiency with solar length at boiler pressure 0.1 [atm] for two cases when the HTF mass flowrate is 0.05 [kg/s], 0.15 [kg/s], and .2 [kg/s] which cause Turbulent flow at Solar collector

However, reaching to the maximum COP for higher HTF mass flowrate is almost impossible because we assume the system is in steady state condition. Therefore, it required the time to get to that situation, and we have the limited time of solar radiation.

Chapter 4: Conclusions

The codes and these analyses developed to help engineers to design a solar powered water purification system with respect to the requirements. The set of equations for energy balances are determined and the solution calculated under our assumptions by specifying three variables and the rest of the system is automatically calculated. The critical parameters for designing this system are the boiler pressure, purified water mass flowrate, HTF mass flowrate, solar collector length and boiler coil length. These parameters could change due to the design limitation or needs, such as the HTF circulation pump, vacuum pump, demanding water, and space limitations. All these calculations are done based on the one inch coper pipe in the solar collector and 3/8-inch copper pipe for boiler coil. Materials and geometries can be changed by the application, but designers should update the material properties as well. The trend would be the same regardless of the materials and geometries. Our analysis shows what the system efficiency is and how the system output is a function of the HTF, HTF mass flowrate and its flow type in the system, length of the solar collector length, geometry of the system, coil and receiver materials, present and speed of the wind, and boiler pressure. These analyses show that to get the better result the flow in the solar collector should be turbulent, the boiler pressure should be minimum. It also demonstrates that the length of the solar collector is a remarkable factor for the design. As the solar collector length, increases the COP of the system will increases as well. However, there is a maximum length that by going beyond that length the COP of the system starts decreasing. It also shows that by increasing the solar length not only the more water vapor produced but also the required boiler coil length decrease that it helps in initial cost of the design. Although, the mass flowrate with the turbulent flow for HTF is calculated, we recommend that the designer avoid using low flow rates that are too close to the laminar to turbulent transition region, and picked the Reynolds in the solar collector above the 2500 for turbulent flow. Reaching the maximum COP for a lot higher HTF mass flowrate is extremely high

In addition, the wind effect is an important factor. Wind reduces the absorbed heat value, which is directly proportional with the system COP, considerably. Hence, we recommend using mirror with deep concave in order to push the focal point into the mirror and consequently receiver pipe moved into the reflector too to reduce the wind effect on the system. Also, apply the glass walls surround the solar part of the system would help significantly.

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Appendix:

Table 4: Values of Cs,f for various surface-fluid combinations

Surface-Fluid Combination	$C_{s,f}$	n
Water-copper		
Scored	0.0068	1
Polished	0.0128	1
Water- Stainless steel		
Chemically etched	0.0133	1
Mechanical Polished	0.0132	1
Ground and polished	0.008	1
Water- brass	0.006	1
Water Nickel	0.006	1
Water Platinum	0.013	1
n-Pentane-copper		
Polished	0.0154	1.7
Lapped	0.0049	1.7
Benzene-Chromium	0.0101	1.7
Ethyl alcohol- Chromium	0.0027	1.7

Code for absorbed Heat in solar collector with wind effect:

```
"Solar Collector"
rho_mirror=.99 "Mirror
reflectivity"
alpha_pipe=1 "Emissivity
Which is equal absorbability. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system. "
"At this stage we eliminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzmann"
T_sun=1373 [K] "Temperature
on top of the atmosphere"
"** Physical Properties of solar collector**"
theta=70 "Angle of the
pipe to the vertical axis "
"L=10.2 [m]" "length of the
pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
```

```
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe radius"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
epsilon_pipe=1
"**Ambient and environmental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperature "
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=(1*convert(atm,Pa)) ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
viscosity in assumed condition "
k_air=conductivity(Air,T=T_avg) "Thermal
Coductivity in assumed condition"
alpha_air=thermaldiffusivity(Air,T=T_avg,P=P_amb)
Beta_air=1/T_avg
g=9.81
"**Heat from the Sun**"
```

File:Solar collector-2-wind effect.EES 8/27/2017 5:55:31 PM Page 2
EES Ver. 10.107: #1935: For use only in the College of Engineering, Santa Clara University

```
Ra_L=g*Beta_air*(cos(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overall convection heat transfer coefficient. ( Based on only natural convection)"
nu_wind=kinematicviscosity(Air_ha,T=T_avg,P=P_amb)
pr_wind=prandtl(Air_ha,T=T_avg,P=P_amb)
pr_Swind=prandtl(Air_ha,T=T_osur,P=P_amb)
Re_wind=10*D_2/nu_wind
C_wind=.26
m_wind=.6
n_wind=.37
NUS_wind=C_wind*(Re_wind^m_wind)*(pr_wind^n_wind)*((pr_wind/pr_Swind)^.25)
h_wind=NUS_wind*k_air/D_2
Q_wind=h_wind*A_pipe*DELTAT
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4-T_amb^4))-
(h_w*A_pipe*DELTAT)-Q_wind "
The total solar heat that goes to the system"
"Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4-T_amb^4))-
(h_w*A_pipe*DELTAT)" "
The total solar heat that goes to the system"
```

```
"Q_in=3986"
"For Heat that Transfer to the HTF by conduction and convection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system "
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(exp((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgF))-
0.000807195*(exp((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
h_F=3.66*k_F/D_1 "Assumed that
there is a laminar flow in the tubes"
R_Ftotal=(ln(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradient. That heat will calculated by following"
m_dot=.05 [kg/s] "HTF Mass flow rate"
Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
    Q_F=Q_in
```

Table 5: properties change with wind effects (wind speed at 36 [km/hr]

	L [m]	Q_{CF}	T_{Fout}	T_{avgF}	T_{osur}
Run 1	10	*1325*	*325.2*	*319.1*	*401.4*
Run 2	10.26	*1384*	*325.8*	*319.4*	*401.1*
Run 3	10.51	*1444*	*326.3*	*319.7*	*400.8*
Run 4	10.77	*1505*	*326.9*	*319.9*	*400.5*
Run 5	11.03	*1566*	*327.4*	*320.2*	*400.3*
Run 6	11.28	*1628*	*328*	*320.5*	*400*
Run 7	11.54	*1691*	*328.6*	*320.8*	*399.8*
Run 8	11.79	*1755*	*329.1*	*321.1*	*399.5*
Run 9	12.05	*1819*	*329.7*	*321.4*	*399.2*
Run 10	12.31	*1884*	*330.3*	*321.7*	*399*
Run 11	12.56	*1949*	*330.9*	*322*	*398.8*
Run 12	12.82	*2015*	*331.5*	*322.3*	*398.5*
Run 13	13.08	*2081*	*332.1*	*322.6*	*398.3*
Run 14	13.33	*2148*	*332.7*	*322.9*	*398.1*
Run 15	13.59	*2216*	*333.3*	*323.2*	*397.8*
Run 16	13.85	*2284*	*333.9*	*323.5*	*397.6*
Run 17	14.1	*2352*	*334.6*	*323.8*	*397.4*
Run 18	14.36	*2420*	*335.2*	*324.1*	*397.2*
Run 19	14.62	*2490*	*335.8*	*324.4*	*397*
Run 20	14.87	*2559*	*336.4*	*324.7*	*396.8*
Run 21	15.13	*2629*	*337.1*	*325*	*396.6*
Run 22	15.38	*2699*	*337.7*	*325.3*	*396.4*
Run 23	15.64	*2769*	*338.3*	*325.7*	*396.2*
Run 24	15.9	*2840*	*339*	*326*	*396*
Run 25	16.15	*2911*	*339.6*	*326.3*	*395.8*
Run 26	16.41	*2982*	*340.2*	*326.6*	*395.6*
Run 27	16.67	*3053*	*340.9*	*326.9*	*395.5*
Run 28	16.92	*3125*	*341.5*	*327.3*	*395.3*
Run 29	17.18	*3197*	*342.2*	*327.6*	*395.1*
Run 30	17.44	*3269*	*342.8*	*327.9*	*395*
Run 31	17.69	*3341*	*343.4*	*328.2*	*394.8*
Run 32	17.95	*3413*	*344.1*	*328.5*	*394.7*
Run 33	18.21	*3486*	*344.7*	*328.9*	*394.5*
Run 34	18.46	*3558*	*345.4*	*329.2*	*394.4*
Run 35	18.72	*3631*	*346*	*329.5*	*394.2*
Run 36	18.97	*3703*	*346.7*	*329.8*	*394.1*
Run 37	19.23	*3776*	*347.3*	*330.2*	*393.9*
Run 38	19.49	*3849*	*348*	*330.5*	*393.8*
Run 39	19.74	*3922*	*348.6*	*330.8*	*393.7*
Run 40	20	*3995*	*349.3*	*331.1*	*393.5*

Code for absorbed Heat in solar collector without wind effect:

```
"Solar Collector"
rho_mirror=.99 "Mirror
reflectivity"
alpha_pipe=1 "Emissivity
which is equal absobivity. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system. "
"At this stage we eliminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzmann"
T_sun=1373 [K] "Temperature
on top of the atmosphere"
"** Physical Properties of solar collector**"
theta=70 "Angle of the
pipe to the vertical axis "
L=10.2 [m] "length of the
pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe
radius"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
epsilon_pipe=1
A_crosspipe= pi*(r_1^2)
"**Ambient and environmental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperature"
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=(1*convert(atm,Pa)) ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
viscosity in assumed condition "
k_air=conductivity(Air,T=T_avg) "Thermal
Coductivity in assumed condition"
alpha_air=thermaldiffusivity(Air,T=T_avg,P=P_amb) "Thermal
```

```
Diffusivity at assumed condition"
Beta_air=1/T_avg "EXPANSION
COEFFICIENT FOR AIR"
```

```
g=9.81 [m/s^2]
"**Heat from the Sun**"
Ra_L=g*Beta_air*(cos(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overal convection heat transfer coefficient. ( Based on only natural convection)"
nu_wind=kinematicviscosity(Air_ha,T=T_avg,P=P_amb)
pr_wind=prandtl(Air_ha,T=T_avg,P=P_amb)
pr_Swind=prandtl(Air_ha,T=T_osur,P=P_amb)
Re_wind=6*D_2/nu_wind
C_wind=.26
m_wind=.6
n_wind=.37
NUS_wind=C_wind*(Re_wind^m_wind)*(pr_wind^n_wind)*((pr_wind/pr_Swind)^.25)
h_wind=NUS_wind*k_air/D_2
Q_wind=h_wind*A_pipe*DELTAT
"Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4-T_amb^4))-
(h_w*A_pipe*DELTAT)-Q_wind" "
The total solar heat that goes to the system"
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4-T_amb^4))-
(h_w*A_pipe*DELTAT) "The total
solar heat that goes to the system"
"Q_in=3986"
"For Heat that Transfer to the HTF by conduction and convection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system "
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(exp((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgF))-
0.000807195*(exp((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
"m_dot=.05 [kg/s]" "HTF Mass
flow rate"
Re_f= m_dot*D_1/(A_crosspipe*mu_f)
Pr_f= C_PF*mu_f/k_F
"NU_F1=.023*(Re_f^(3/4))*Pr_f^.4"
h_F=3.66*k_F/D_1 "Assumed that
there is a laminar flow in the tubes"
R_Ftotal=(ln(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
```

transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradient. That heat will calculated by following"

Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
Q_F=Q_in

Table 6: Properties change without wind effects

	L [m]	Q_{CF}	T_{Fout}	T_{avgF}	T_{osur}
Run 1	10	3839	347.9	330.4	570.2
Run 2	10.26	4002	349.3	331.2	568.8
Run 3	10.51	4166	350.8	331.9	567.5
Run 4	10.77	4333	352.2	332.6	566.2
Run 5	11.03	4500	353.7	333.4	564.9
Run 6	11.28	4669	355.2	334.1	563.6
Run 7	11.54	4840	356.7	334.9	562.4
Run 8	11.79	5012	358.2	335.6	561.2
Run 9	12.05	5185	359.7	336.4	560
Run 10	12.31	5359	361.2	337.1	558.8
Run 11	12.56	5534	362.8	337.9	557.6
Run 12	12.82	5710	364.3	338.7	556.5
Run 13	13.08	5887	365.8	339.4	555.4
Run 14	13.33	6065	367.4	340.2	554.3
Run 15	13.59	6244	368.9	341	553.2
Run 16	13.85	6423	370.5	341.7	552.2
Run 17	14.1	6603	372	342.5	551.1
Run 18	14.36	6784	373.6	343.3	550.1
Run 19	14.62	6966	375.1	344.1	549.1
Run 20	14.87	7148	376.7	344.8	548.2
Run 21	15.13	7331	378.2	345.6	547.2
Run 22	15.38	7514	379.8	346.4	546.3
Run 23	15.64	7697	381.4	347.2	545.3
Run 24	15.9	7881	382.9	348	544.4
Run 25	16.15	8066	384.5	348.7	543.6
Run 26	16.41	8250	386	349.5	542.7
Run 27	16.67	8435	387.6	350.3	541.9
Run 28	16.92	8621	389.2	351.1	541
Run 29	17.18	8806	390.7	351.9	540.2
Run 30	17.44	8992	392.3	352.6	539.4
Run 31	17.69	9178	393.8	353.4	538.7
Run 32	17.95	9364	395.4	354.2	537.9
Run 33	18.21	9550	396.9	355	537.2
Run 34	18.46	9736	398.5	355.7	536.5
Run 35	18.72	9923	400	356.5	535.7
Run 36	18.97	10109	401.6	357.3	535.1
Run 37	19.23	10296	403.1	358.1	534.4
Run 38	19.49	10482	404.7	358.8	533.7
Run 39	19.74	10669	406.2	359.6	533.1
Run 40	20	10855	407.7	360.4	532.4

Code for finding Reynolds at the solar collector:

```
    "** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg)                                   "Viscosity of air at T_avg"
rho_air=density(Air,T=T_avg,P=(1*convert(atm,Pa)) )             "Density of the air at T_avg and,
pressure at1 atm "

nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb)                  "Kinematic viscosity in assumed
condition "
k_air=conductivity(Air,T=T_avg)                                 "Thermal Coductivity in assumed
condition"
alpha_air=thermaldiffusivity(Air,T=T_avg,P=P_amb)               "Thermal Diffusivity at assumed
condition"
Beta_air=1/T_avg                                                "EXPANSION COEFFICIENT FOR
AIR"
g=9.81 [m/s^2]

"**Heat from the Sun**"

Ra_L=g*Beta_air*(cos(theta))*DELTAT*(L^3)/(nu_air*alpha_air)    "Rayleigh number for length the
tube "
h_w=.524*k_air*(Ra_L^.25)/L                                     "Average overal convection heat
transfer coefficient. ( Based on only natural convection)"

nu_wind=kinematicviscosity(Air_ha,T=T_avg,P=P_amb)
pr_wind=prandtl(Air_ha,T=T_avg,P=P_amb)
pr_Swind=prandtl(Air_ha,T=T_osur,P=P_amb)
Re_wind=6*D_2/nu_wind
C_wind=.26
m_wind=.6
n_wind=.37
NUS_wind=C_wind*(Re_wind^m_wind)*(pr_wind^n_wind)*((pr_wind/pr_Swind)^.25)
h_wind=NUS_wind*k_air/D_2
Q_wind=h_wind*A_pipe*DELTAT
```

```
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4-T_amb^4))-(h_w*A_pipe*DELTAT)   "The total solar heat that goes to the system"


"For Heat that Transfer to the HTF by conduction and convection"

    "**HTF Properties**"
T_Fin=313[K]                                                        "Inlet HTF Temperature to the solar collector system "
"T_Fout=413 "                                                       "Outlet HTF Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2                                             "Average Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-5.02057*(exp((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
 nu_f=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgF))-0.000807195*(exp((373/T_avgF)^2))+0.00104979*exp((373/T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-06*T_avgF^3

"m_dot=.05 [kg/s]"                                                  "HTF Mass flow rate"
Re_f= m_dot*D_1/(A_crosspipe*mu_f)
Pr_f= C_PF*mu_f/k_F
"NU_F1=.023*(Re_f^(3/4))*Pr_f^.4"

h_F=3.66*k_F/D_1                                                    "Assumed that there is a laminar flow in the tubes"
R_Ftotal=(ln(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F))          "Total heat transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
 Q_CF=(A_pipe/R_Ftotal)*DELTAT_F                                    "Heat that transferredto HTF by Convection"

Q_CF=Q_in

"Heat which is computed based on temperature gradient. That heat will calculated by following"


Q_F=m_dot*C_PF*(T_Fout-T_Fin)                 "Amount of heat that is involved increasing HTF temperature"
Q_F=Q_in
```

Table 7: relation between the mass flow rate and Re at the solar collector

	m [kg/s]	Re_f
Run 9	0.1747	*2476*
Run 10	0.1747	*2477*
Run 11	0.1748	*2478*
Run 12	0.1749	*2479*
Run 13	0.175	*2480*
Run 14	0.1751	*2481*
Run 15	0.1751	*2482*
Run 16	0.1752	*2483*
Run 17	0.1753	*2484*
Run 18	0.1754	*2485*
Run 19	0.1755	*2486*
Run 20	0.1756	*2487*
Run 21	0.1756	*2488*
Run 22	0.1757	*2489*
Run 23	0.1758	*2490*
Run 24	0.1759	*2491*
Run 25	0.176	*2492*
Run 26	0.176	*2493*
Run 27	0.1761	*2494*
Run 28	0.1762	*2495*
Run 29	0.1763	*2496*
Run 30	0.1764	*2497*
Run 31	0.1764	*2498*
Run 32	0.1765	*2499*
Run 33	0.1766	*2500*
Run 34	0.1767	*2501*
Run 35	0.1768	*2502*
Run 36	0.1769	*2503*
Run 37	0.1769	*2504*
Run 38	0.177	*2506*
Run 39	0.1771	*2507*
Run 40	0.1772	*2508*
Run 41	0.1773	*2509*
Run 42	0.1773	*2510*
Run 43	0.1774	*2511*
Run 44	0.1775	*2512*
Run 45	0.1776	*2513*
Run 46	0.1777	*2514*
Run 47	0.1778	*2515*
Run 48	0.1778	*2516*
Run 49	0.1779	*2517*
Run 50	0.178	*2518*

Code for solving Boiler:

```
  "BOILER: "
"Assume the flow in the tube is turbulent "
"Boiler has two components, Coil and boiler container. The HOT HTF flows through the coils and loss heat and Salt water boil by nucleate boiling "
"Coil is made by 3/8 in copper pipe"
" We assume HTF leave the boiler at the 90C temperature"
"We are going to make three equations for heat and balance them for computing all variable "
"Firs heat we are going to calculate is the heat that the HTF loss by passing through the coil in the boiler "
"Second we will calculating the heat flux that goes from the HTF by conduction to the salt water "
"Last one is the heat that which is caused increasing the inlet salt water temperature and boiling the salt water, and it is include the heat lost
through the boiler body to the environment"

"FACTS "
m_dot=.024 [kg/m^3]                                                    "It is same amount of HTF mass
flow rate in solar collector "
 g=9.81 [m/s^2]                                                        "Gravity "

"COIL Features "
L_coil=2*25.92*convert(ft,m)                                           "Coil lenght "
D_1coil=.375*convert(in,m)                                             "Coil ID"
r_1coil=D_1coil/2
D_2coil=.5*convert(in,m)                                               "Coil OD"
r_2coil=D_2coil/2
K_coil=400 [W/m*K]                                                     "Thermal conductivity factor "
A_coil1=pi*(D_1coil^2)/4                                               "Coil Inner surface area "
A_coil2=pi*(D_2coil^2)/4                                               "Coil Outer surface area"
 A_crosscoil=(D_1coil^2)*pi/4
P_2coil=pi*D_2coil                                                     "Outter coil Perimeter"
A_2coilsurface=P_2coil*L_coil

" Calculate properties of the HTF"

mu_0f=1.44*10^(-3)                                                     "HTF Dynamic Viscosity at 100C"
T_0=373 [K]                                                            "Oregin HTF Temp for property
calculation"
```

```
nu_0f=1.78*10^(-6)                                  "HTF Kinematic Viscosity @ 100C"
k_0f=.138                                           "HTF Thermal Conductivity @ 100
C_p0f=2330                                          "HTF heat capacity (Cp) @ 100 C"

" We introduce T_avgFB. this is the average of the temperature of HTF inlet and outlet.
Temperature of the oule let is assumed, T_fout=80 C"

"T_fout=(90+273)"                                   "HTF outlet temperature "
T_fin=401.6
T_avgFB=(T_fout+T_fin)/2                            "HTF Average temperature in the
coil"

"T_avgFB=130+273"

"Use Look Up Table "

mu_fb=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgFB))-5.02057*(exp((373/T_avgFB)^2))+2.31971*exp((373/T_avgFB)^3))

nu_fb=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgFB))-0.000807195*(exp((373/T_avgFB)^2))+0.00104979*exp((373/T_avgFB)^3))

k_fb=1.44720528E-01+8.23925584E-05*T_avgFB-3.99012752E-07*T_avgFB^2+3.42794460E-10*T_avgFB^3

c_pfb=1.27992524E+03+2.45018746E+00*T_avgFB+1.37430217E-03*T_avgFB^2-1.06266283E-06*T_avgFB^3

Pr_fb=C_pfb*mu_fb/k_fb                              "HTF Prandtle at T_avgFB"
Re_fb=m_dot*d_1coil/(A_crosscoil*mu_fb)             "HTF Reynolds inside the coil tube "
Nu_Dfb=.0265*(Re_fb^(4/5))*(Pr_fb^.3)

" This Nuselt is calculated for turbulent flow while it gets cool"
h_fb=Nu_Dfb*k_fb/D_1coil
                                                    "HTF Convection heat ttransfer
coefficient inside the coil tube. "

Q_fb=m_dot*C_pfb*(T_fin-T_fout)                     "Energy HTF equation "

"Conduction Heat Transfer"
"The heat flux from HTF to the outer surface of the coil tube"
"We introduce T_cbs, which is temperature on the outer surface of the coil tube"
"T_cbs=383"
```

```
R_totalFSB=((ln(r_2coil/r_1coil))/(2*pi*K_coil*L_coil))+(1/(2*pi*r_1coil*L_coil*h_fb))        "Total Thermal resistance for HTF and coil thickness"
Q_FSB=(T_avgFB-T_cbs)/R_totalFSB        "Heat flux through convection and conduction from HTF to surface of the coil tube"

"Nucleate Boiling heat transfer "
"We assume the heat lost is negligible because of good insulation. this heat is consist the heat which is caused the boiling and increasing the temperature  of the inlet salt water to the saturation temperature."
"We assume the system is steady state and amount of the mass flow rate is equal to the amount of water which is vaporized.  "

"Water Properties"

C_SF=.0128
 " P_water is pressure of the boiler"
T_sat=t_sat(Water,P=(P_water*convert(atm,Pa)) )
DELTAh_vap=enthalpy_vaporization(Water,T=T_sat)
mu_fwater=viscosity(Water,T=T_sat,x=0)
v_fwater=volume(Water,T=T_sat,x=0)
cp_fwater=specheat(Water,T=T_sat,x=0)
Pr_fwater=prandtl(Water,T=T_sat,x=0)
rho_fwater=density(Water,T=T_sat,x=0)

rho_gwater=density(Water,T=T_sat,x=1)

sigma_fwater=surfacetension(Water,T=T_sat)
T_waterinlet=313

cp=cp(Water,T=T_waterinlet,x=0)

"Nucleate boiling heat per square  meter"
q_s=mu_fwater*DELTAh_vap*((g*(rho_fwater-rho_gwater)/sigma_fwater)^.5)*((cp_fwater*(T_cbs-T_sat)/(C_SF*DELTAh_vap*Pr_fwater))^3)
q_sReal=q_s*A_2coilsurface        "Real nucleate boiling "
m_dot_v=q_sReal/DELTAh_vap

"The total heat that transferredto the boiler is:"
Q_SB=q_sReal+m_dot_v*cp*(T_sat-T_waterinlet)

"All Heat are equal to each other "
Q_fb=Q_FSB
Q_fb=Q_SB
```

Table 8: Boiler solution T=401.6&P=.05-1.1

	P_{water}	Q_{fb}	T_{avgFB}	T_{cbs}	T_{fin}	T_{sat}
Run 1	0.05	*9102*	*362*	*314.1*	*401.6*	*306.3*
Run 2	0.1053	*7819*	*367.8*	*328.2*	*401.6*	*320.2*
Run 3	0.1605	*7004*	*371.5*	*336.7*	*401.6*	*328.8*
Run 4	0.2158	*6404*	*374.2*	*342.9*	*401.6*	*335.2*
Run 5	0.2711	*5963*	*376.1*	*347.3*	*401.6*	*340.2*
Run 6	0.3263	*5582*	*377.8*	*351.1*	*401.6*	*344.5*
Run 7	0.3816	*5245*	*379.3*	*354.4*	*401.6*	*348.2*
Run 8	0.4368	*4942*	*380.6*	*357.3*	*401.6*	*351.5*
Run 9	0.4921	*4666*	*381.8*	*359.9*	*401.6*	*354.4*
Run 10	0.5474	*4412*	*382.9*	*362.4*	*401.6*	*357.1*
Run 11	0.6026	*4175*	*383.9*	*364.6*	*401.6*	*359.5*
Run 12	0.6579	*3954*	*384.9*	*366.7*	*401.6*	*361.8*
Run 13	0.7132	*3747*	*385.8*	*368.6*	*401.6*	*363.9*
Run 14	0.7684	*3550*	*386.6*	*370.4*	*401.6*	*365.9*
Run 15	0.8237	*3364*	*387.4*	*372.1*	*401.6*	*367.8*
Run 16	0.8789	*3187*	*388.2*	*373.7*	*401.6*	*369.6*
Run 17	0.9342	*3018*	*388.9*	*375.3*	*401.6*	*371.3*
Run 18	0.9895	*2856*	*389.6*	*376.8*	*401.6*	*372.9*
Run 19	1.045	*2700*	*390.3*	*378.2*	*401.6*	*374.4*
Run 20	1.1	*2551*	*390.9*	*379.5*	*401.6*	*375.8*

Table 9: Variable limit and guess value

Variable	Guess	Lower	Upper	Units	Comment
alpha_air	1.000E+00	-infinity	infinity		
alpha_pipe	1.000E+00	*-infinity*	*infinity*		
A_2coilsurface	1.000E+00	-infinity	infinity		
A_coil1	7.126E-05	*-infinity*	*infinity*		
A_coil2	1.267E-04	*-infinity*	*infinity*		
A_crosscoil	7.126E-05	*-infinity*	*infinity*		
A_mirror	1.000E+00	0.0000E+00	infinity		
A_pipe	1.000E+00	0.0000E+00	infinity		
Beta_air	1.000E+00	-infinity	infinity		
COP	1.000E+00	-infinity	infinity		
cp	4.182E+03	*-infinity*	*infinity*		
cp_fwater	4.182E+03	*-infinity*	*infinity*		
C_PF	2.155E+03	5.0000E+02	infinity		
c_pfb	1.000E+00	-infinity	infinity		
C_SF	1.280E-02	*-infinity*	*infinity*		
DELTAh_vap	2.391E+06	*-infinity*	*infinity*		
DELTAT	1.000E+00	0.0000E+00	infinity		
DELTAT_F	1.000E+00	0.0000E+00	infinity		
D_1	2.540E-02	*-infinity*	*infinity*	m	
D_1coil	9.525E-03	*-infinity*	*infinity*	m	
D_2	3.150E-02	*-infinity*	*infinity*	m	
D_2coil	1.270E-02	*-infinity*	*infinity*	m	
epsilon_pipe	1.000E+00	*-infinity*	*infinity*		
g	9.810E+00	*-infinity*	*infinity*	m/s^2	
h_F	1E+00	0.0000E+00	infinity		
h_fb	1E+00	-infinity	infinity		
h_w	1E+00	0.0000E+00	infinity		
k_air	1.000E+00	0.0000E+00	2.0000E+00		
K_coil	4.000E+02	*-infinity*	*infinity*	W/m*K	
k_cop	4.000E+02	*-infinity*	*infinity*	W/(m*K)	
k_F	1.000E+00	0.0000E+00	1.0000E+01		
k_fb	1.000E+00	-infinity	infinity		
L	1.930E+01	0.0000E+00	infinity	m	
L_coil	1.580E+01	0.0000E+00	infinity	m	
mu_air	5.000E-01	0.0000E+00	5.0000E-01		
mu_f	5.000E-01	0.0000E+00	5.0000E-01		
mu_fb	1.000E+00	0.0000E+00	infinity		
mu_fwater	5.851E-04	*0.0000E+00*	*infinity*		
m_dot	5.000E-02	*-infinity*	*infinity*	kg/s	
m_dot_v	1.000E+00	-infinity	infinity		
nu_air	1.000E-04	0.0000E+00	1.0000E-04		
Nu_Dfb	7.000E+01	0.0000E+00	3.0000E+02		
nu_f	1.000E+00	-infinity	infinity		
nu_fb	1.000E+00	-infinity	infinity		
Pr_fb	1E+00	0.0000E+00	1.0000E+02		
Pr_fwater	3E+00	*0.0000E+00*	*3.0000E+00*		
P_2coil	4E-02	*-infinity*	*infinity*		
P_amb	1E+05	*-infinity*	*infinity*	Pa	
P_water	1E-01	*0.0000E+00*	*1.4000E+00*	atm	

Q_CF	1.0E+04	-infinity	infinity
Q_F	1.0E+04	-infinity	infinity
Q_fb	1.0E+00	-infinity	infinity
Q_FSB	1.0E+00	-infinity	infinity
Q_in	1.0E+00	-infinity	infinity
q_s	1.0E+00	0.0000E+00	infinity

Q_SB	1.0E+00	-infinity	infinity	
q_sReal	1.0E+00	0.0000E+00	infinity	
Q_sun	1.0E+00	-infinity	infinity	
Ra_L	1.000E+00	0.0000E+00	infinity	
Re_fb	1.000E+03	0.0000E+00	1.0000E+05	
rho_air	1.000E+00	-infinity	infinity	
rho_fwater	9.897E+02	*-infinity*	*infinity*	
rho_gwater	6.900E-02	*-infinity*	*infinity*	
rho_mirror	9.900E-01	*-infinity*	*infinity*	
r_1	1.270E-02	*-infinity*	*infinity*	
r_1coil	4.763E-03	*-infinity*	*infinity*	
r_2	1.575E-02	*-infinity*	*infinity*	
r_2coil	6.350E-03	*-infinity*	*infinity*	
R_Ftotal	1.000E+00	-infinity	infinity	
R_totalFSB	1.000E+00	-infinity	infinity	
Sigma	5.670E-08	*-infinity*	*infinity*	
sigma_fwater	6.860E-02	*-infinity*	*infinity*	
theta	7.0E+01	*-infinity*	*infinity*	
T_amb	2.9E+02	*-infinity*	*infinity*	K
T_avg	3.0E+02	0.0000E+00	infinity	
T_avgF	3.6E+02	2.7300E+02	infinity	
T_avgFB	3.6E+02	3.0000E+02	5.0000E+02	
T_cbs	3.3E+02	3.0000E+02	5.0000E+02	
T_Fin	3.1E+02	*2.9300E+02*	*infinity*	K
T_finB	4.0E+02	-infinity	infinity	
T_Fout	4.0E+02	3.0000E+02	infinity	
T_foutB	3.0E+02	3.0000E+02	5.0000E+02	
T_osur	5.3E+02	2.7300E+02	infinity	
T_sat	3.2E+02	*3.0000E+02*	*infinity*	
T_sun	1.4E+03	*-infinity*	*infinity*	K
T_waterinlet	3.1E+02	*2.7300E+02*	*infinity*	
v_fwater	1.010E-03	*-infinity*	*infinity*	

Code for System when flow is Laminar in the solar collector, $\dot{m}_V$ changes, ($\dot{m} = .05\ \left[\frac{kg}{s}\right]$, $P_{Boiler} = .1\ [atm]$):

```
"Solar Collector"
rho_mirror=.99 "Mirror
reflectivity"
alpha_pipe=1 "Emissivity
which is equal absobility. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system. "
"At this stage we eliminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzman"
T_sun=1373 [K] "Temperature
on top of the atmosphere"
"** Physical Properties of solar collector**"
theta=70 "Angle of the
pipe to the vertical axis "
"L=30*convert(ft,m) " "length of the
pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe
radias"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
epsilon_pipe=1
"**Ambient and environmental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperature "
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=P_amb ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
viscosity in assumed condition "
k_air=conductivity(Air,T=T_avg) "Thermal
Coductivity in assumed condition"
```

```
alpha_air=thermaldiffusivity(Air,T=T_avg,P=P_amb) "Thermal
Diffusivity at assumed condition"
Beta_air=1/T_avg "EXPANSION
COEFFICIENT FOR AIR"
g=9.81 [m/s^2]
File:Solar collector-Boiler-M_dot_v variable.EES 8/28/2017 2:10:22 PM Page 2
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"**Heat from the Sun**"
Ra_L=g*Beta_air*(cos(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overal convection heat transfer coefficient. ( Based on only natural convection)"
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4))-(h_w*A_pipe*DELTAT) "The
heat that
will conduct to the HTF"
"Q_in=2900"
"For Heat that Transfer to the HTF by conduction and convection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system "
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(exp((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgF))-
0.000807195*(exp((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
h_F=3.66*k_F/D_1 "Assumed that
there is a laminar flow in the tubes"
R_Ftotal=(ln(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradient. That heat will calculated by following"
m_dot=.05 [kg/s] "HTF Mass flow rate"
Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
Q_F=Q_in
"BOILER: "
"Assume the flow in the tube is turbulent "
"Boiler has two components, Coil and boiler container. The HOT HTF flows through the coils and loss
heat and Salt water
boil by nucleate boiling "
"Coil is made by 3/8 in copper pipe"
" We assume HTF leave the boiler at the 90C temperature"
"We are going to make three equations for heat and balance them for computing all variable "
"Firs heat we are going to calculate is the heat that the HTF loss by passing through the coil in the boiler "
"Second we will calculating the heat flux that goes from the HTF by conduction to the salt water "
```

"Last one is the heat that which is caused increasing the inlet salt water temperature and boiling the salt water, and it is
include the heat lost through the boiler body to the environment"
"FACTS "
"m_dot" "It is same

amount of HTF mass flow rate in solar collector "
"COIL Features "
"L_coil=25.92*convert(ft,m)" "Coil length "
D_1coil=.375***convert**(in,m) "Coil ID"
r_1coil=D_1coil/2
D_2coil=.5***convert**(in,m) "Coil OD"
r_2coil=D_2coil/2
K_coil=400 [W/m*K] "Thermal
conductivity factor "
A_coil1=pi*(D_1coil^2)/4 "Coil Inner
surface area "
A_coil2=pi*(D_2coil^2)/4 "Coil Outer
surface area"
A_crosscoil=(D_1coil^2)*pi/4
P_2coil=pi*D_2coil "Outter coil
Perimeter"
A_2coilsurface=P_2coil*L_coil
" We introduce T_avgFB. this is the average of the temperature of HTF inlet and outlet.
Temperature of the oule let is assumed, T_foutB=80 C"
"T_foutB=(90+273)" "HTF outlet
temperature "
T_finB=T_Fout
T_avgFB=(T_foutB+T_finB)/2 "HTF Average
Temperature in the coil"
"T_avgFB=332"
"Use Look Up Table "
mu_fb=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgFB))-
5.02057*(**exp**((373/T_avgFB)^2))+2.31971*exp((373/T_avgFB)^3))
nu_fb=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgFB))-
0.000807195*(**exp**((373/T_avgFB)^2))+0.00104979*exp((
373/T_avgFB)^3))
k_fb=1.44720528E-01+8.23925584E-05*T_avgFB-3.99012752E-07*T_avgFB^2+3.42794460E-
10*T_avgFB^3
c_pfb=1.27992524E+03+2.45018746E+00*T_avgFB+1.37430217E-03*T_avgFB^2-1.06266283E-
06*T_avgFB^3
Pr_fb=C_pfb*mu_fb/k_fb "HTF Prandtle
at T_avgFB"
Re_fb=m_dot*d_1coil/(A_crosscoil*mu_fb) "HTF Reynolds
inside the coil tube "
Nu_Dfb=.0265*(Re_fb^(4/5))*(Pr_fb^.3)
" This Nuselt is calculated for turbulent flow while it gets cool"
h_fb=Nu_Dfb*k_fb/D_1coil
"HTF
Convection heat ttransfer coefficient inside the coil tube. "
Q_fb=m_dot*C_pfb*(T_finB-T_foutB) "Energy HTF
equation "
"Conduction Heat Transfer"
"The heat flux from HTF to the outer surface of the coil tube"
"We introduce T_cbs, which is temperature on the outer surface of the coil tube"

```
"T_cbs=325"
R_totalFSB=((ln(r_2coil/r_1coil))/(2*pi*K_coil*L_coil))+(1/(2*pi*r_1coil*L_coil*h_fb)) "Total Thermal
resistance for HTF and coil thickness"
File:Solar collector-Boiler-M_dot_v variable.EES 8/28/2017 2:10:22 PM Page 4
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Q_FSB=(T_avgFB-T_cbs)/R_totalFSB "Heat flux
through convection and conduction from HTF to surface of the coil tube"
Q_fb=Q_FSB
"Nucleate Boiling heat transfer "
"We assume the heat lost is negligible because of good insulation. this heat is consist the heat which is
caused the boiling
and increasing the temperature of the inlet salt water to the saturation temperature."
"We assume the system is steady state and amount of the mass flow rate is equal to the amount of water
which is vaporized.
"
"Water Properties"
C_SF=.0128
" P_water is pressure of the boiler"
P_water= .1 [atm]
T_sat=t_sat(Water,P=(P_water*convert(atm,Pa)) )
DELTAh_vap=enthalpy_vaporization(Water,T=T_sat)
mu_fwater=viscosity(Water,T=T_sat,x=0)
v_fwater=volume(Water,T=T_sat,x=0)
cp_fwater=specheat(Water,T=T_sat,x=0)
Pr_fwater=prandtl(Water,T=T_sat,x=0)
rho_fwater=density(Water,T=T_sat,x=0)
rho_gwater=density(Water,T=T_sat,x=1)
sigma_fwater=surfacetension(Water,T=T_sat)
T_waterinlet=313
cp=cp(Water,T=T_waterinlet,x=0)
"Nucleate boiling heat per square e meter"
q_s=mu_fwater*DELTAh_vap*((g*(rho_fwater-rho_gwater)/sigma_fwater)^.5)*((cp_fwater*(T_cbs-
T_sat)/(C_SF*
DELTAh_vap*Pr_fwater))^3)
q_sReal=q_s*A_2coilsurface "Real
nucleate boiling "
m_dot_v=q_sReal/DELTAh_vap
"m_dot_v=.004336"
"The total heat that transferred to the boiler is:"
Q_SB=q_sReal+m_dot_v*cp*(T_sat-T_waterinlet)
"All Heat are equal to each other "
Q_fb=Q_SB
Q_fb=Q_F
"**Efficiency**"
Q_sun=1000*A_mirror
    COP= m_dot_v*DELTAh_vap/Q_sun
```

Table 10: result table for laminar flow at solar collector

	m_v	m	P_{water}	L	Q_{CF}	T_{avgF}	T_{avgFB}	T_{finB}	T_{cbs}	T_{osur}	T_{sat}	T_{foutB}	L_{coil}	COP
		[kg/s]	[atm]	[m]									[m]	
Run 1	0.007	0.05	0.1	29.31	16921	384.6	384.6	456.1	328.4	511	319.2	313	10.99	0.5692
Run 2	0.0064	0.05	0.1	27.16	15471	378.9	378.9	444.8	328	513.2	319.2	313	11.42	0.5617
Run 3	0.0058	0.05	0.1	25.03	14021	373.2	373.2	433.3	327.6	516	319.2	313	11.94	0.5522
Run 4	0.0052	0.05	0.1	22.94	12570	367.4	367.4	421.7	327.2	519.4	319.2	313	12.56	0.5403
Run 5	0.0046	0.05	0.1	20.86	11120	361.5	361.5	409.9	326.7	523.5	319.2	313	13.34	0.5255
Run 6	0.004	0.05	0.1	18.79	9669	355.5	355.5	397.9	326.2	528.6	319.2	313	14.34	0.5073
Run 7	0.0034	0.05	0.1	16.72	8219	349.4	349.4	385.8	325.6	534.7	319.2	313	15.7	0.4846
Run 8	0.0028	0.05	0.1	14.63	6769	343.2	343.2	373.4	325	542	319.2	313	17.71	0.4562
Run 9	0.0022	0.05	0.1	12.48	5318	336.9	336.9	360.9	324.2	550.9	319.2	313	21.11	0.4202
Run 10	0.0016	0.05	0.1	10.22	3868	330.6	330.6	348.1	323.3	561.9	319.2	313	28.55	0.3732
Run 11	0.001	0.05	0.1	7.73	2417	324.1	324.1	335.2	321.9	576	319.2	313	63.59	0.3083

Code for System when flow is Laminar in the solar collector, $\dot{m}$ changes, ($\dot{m}_V = 0.004336\ \left[\frac{kg}{s}\right], P_{Boiler}\ = 0.1\ [atm]$):

```
"Solar Collector"
rho_mirror=.99 "Mirror
Reflectivity"
alpha_pipe=1 "Emissivity
which is equal absobility. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system. "
"At this stage we eliminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzman"
T_sun=1373 [K] "Temperature
on top of the atmosphier"
"** Physical Properties of solar collector**"
theta=70 "Angle of the
pipe to the vertical axis "
"L=30*convert(ft,m) " "length of the
pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe
radias"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
epsilon_pipe=1
"**Ambient and environmental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperature "
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=P_amb ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
viscosity in assumed condition "
k_air=conductivity(Air,T=T_avg) "Thermal
Coductivity in assumed condition"
```

```
alpha_air=thermaldiffusivity(Air,T=T_avg,P=P_amb) "Thermal
Diffusivity at assumed condition"
Beta_air=1/T_avg "EXPANSION
COEFFICIENT FOR AIR"
g=9.81 [m/s^2]
```

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```
"**Heat from the Sun**"
Ra_L=g*Beta_air*(cos(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overall convection heat transfer coefficient. (Based on only natural convection)"
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4))-(h_w*A_pipe*DELTAT) "The
heat that
will conduct to the HTF"
"Q_in=2900"
"For Heat that Transfer to the HTF by conduction and convection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system"
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(exp((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgF))-
0.000807195*(exp((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
h_F=3.66*k_F/D_1 "Assumed that
there is a laminar flow in the tubes"
R_Ftotal=(ln(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradient. That heat will calculated by following"
"m_dot=.05 [kg/s]" "HTF Mass flow rate"
Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
Q_F=Q_in
"BOILER: "
"Assume the flow in the tube is turbulent "
"Boiler has two components, Coil and boiler container. The HOT HTF flows through the coils and loss
heat and Salt water
boil by nucleate boiling "
"Coil is made by 3/8 in copper pipe"
" We assume HTF leave the boiler at the 90C temperature"
"We are going to make three equations for heat and balance them for computing all variable "
"Firs heat we are going to calculate is the heat that the HTF loss by passing through the coil in the boiler "
"Second we will calculating the heat flux that goes from the HTF by conduction to the salt water "
```

```
"Last one is the heat that which is caused increasing the inlet salt water temperature and boiling the salt
water, and it is
include the heat lost through the boiler body to the environment"
"FACTS "
"m_dot" "It is same
```



```
amount of HTF mass flow rate in solar collector "
"COIL Features "
"L_coil=25.92*convert(ft,m)" "Coil lenght "
D_1coil=.375*convert(in,m) "Coil ID"
r_1coil=D_1coil/2
D_2coil=.5*convert(in,m) "Coil OD"
r_2coil=D_2coil/2
K_coil=400 [W/m*K] "Thermal
conductivity factor "
A_coil1=pi*(D_1coil^2)/4 "Coil Inner
surface area "
A_coil2=pi*(D_2coil^2)/4 "Coil Outer
surface area"
A_crosscoil=(D_1coil^2)*pi/4
P_2coil=pi*D_2coil "Outter coil
Perimeter"
A_2coilsurface=P_2coil*L_coil
" We introduce T_avgFB. this is the average of the temperature of HTF inlet and outlet.
Temperature of the oule let is assumed, T_foutB=80 C"
"T_foutB=(90+273)" "HTF outlet
temperature "
T_finB=T_Fout
T_avgFB=(T_foutB+T_finB)/2 "HTF Average
temperature in the coil"
"T_avgFB=332"
"Use Look Up Table "
mu_fb=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgFB))-
5.02057*(exp((373/T_avgFB)^2))+2.31971*exp((373/T_avgFB)^3))
nu_fb=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgFB))-
0.000807195*(exp((373/T_avgFB)^2))+0.00104979*exp((
373/T_avgFB)^3))
k_fb=1.44720528E-01+8.23925584E-05*T_avgFB-3.99012752E-07*T_avgFB^2+3.42794460E-
10*T_avgFB^3
c_pfb=1.27992524E+03+2.45018746E+00*T_avgFB+1.37430217E-03*T_avgFB^2-1.06266283E-
06*T_avgFB^3
Pr_fb=C_pfb*mu_fb/k_fb "HTF Prandtle
at T_avgFB"
Re_fb=m_dot*d_1coil/(A_crosscoil*mu_fb) "HTF Reynolds
inside the coil tube "
Nu_Dfb=.0265*(Re_fb^(4/5))*(Pr_fb^.3)
" This Nuselt is calculated for turbulent flow while it gets cool"
h_fb=Nu_Dfb*k_fb/D_1coil
"HTF
Convection heat ttransfer coefficient inside the coil tube. "
Q_fb=m_dot*C_pfb*(T_finB-T_foutB) "Energy HTF
equation "
"Conduction Heat Transfer"
"The heat flux from HTF to the outer surface of the coil tube"
"We introduce T_cbs, which is temperature on the outer surface of the coil tube"
```

```
"T_cbs=325"
R_totalFSB=((ln(r_2coil/r_1coil))/(2*pi*K_coil*L_coil))+(1/(2*pi*r_1coil*L_coil*h_fb)) "Total Thermal
resistance for HTF and coil thickness"
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Q_FSB=(T_avgFB-T_cbs)/R_totalFSB "Heat flux
through convection and conduction from HTF to surface of the coil tube"
Q_fb=Q_FSB
"Nucleate Boiling heat transfer "
"We assume the heat lost is negligible because of good insulation. this heat is consist the heat which is
caused the boiling
and increasing the temperature of the inlet salt water to the saturation temperature."
"We assume the system is steady state and amount of the mass flow rate is equal to the amount of water
which is vaporized.
"
"Water Properties"
C_SF=.0128
" P_water is pressure of the boiler"
P_water= .1 [atm]
T_sat=t_sat(Water,P=(P_water*convert(atm,Pa)) )
DELTAh_vap=enthalpy_vaporization(Water,T=T_sat)
mu_fwater=viscosity(Water,T=T_sat,x=0)
v_fwater=volume(Water,T=T_sat,x=0)
cp_fwater=specheat(Water,T=T_sat,x=0)
Pr_fwater=prandtl(Water,T=T_sat,x=0)
rho_fwater=density(Water,T=T_sat,x=0)
rho_gwater=density(Water,T=T_sat,x=1)
sigma_fwater=surfacetension(Water,T=T_sat)
T_waterinlet=313
cp=cp(Water,T=T_waterinlet,x=0)
"Nucleate boiling heat per square meter"
q_s=mu_fwater*DELTAh_vap*((g*(rho_fwater-rho_gwater)/sigma_fwater)^.5)*((cp_fwater*(T_cbs-
T_sat)/(C_SF*
DELTAh_vap*Pr_fwater))^3)
q_sReal=q_s*A_2coilsurface "Real
nucleate boiling "
m_dot_v=q_sReal/DELTAh_vap
m_dot_v=.004336
"The total heat that transferred to the boiler is:"
Q_SB=q_sReal+m_dot_v*cp*(T_sat-T_waterinlet)
"All Heat are equal to each other "
Q_fb=Q_SB
Q_fb=Q_F
"**Efficiency**"
Q_sun=1000*rho_mirror*A_mirror ;
COP= m_dot_v*DELTAh_vap/Q_sun
```

Table 11: Laminar flow in solar collector, ṁ changes (ṁ_V=0.004336 [kg/s],P_(Boiler)=0.1 [atm] Constant)

	m	P_{water}	L	Q_{CF}	T_{avgF}	T_{avgFB}	T_{finB}	T_{cbs}	T_{osur}	T_{sat}	T_{foutB}	L_{coil}	m_v	COP
	[kg/s]	[atm]	[m]									[m]		
Run 1	0.05	0.1	19.95	10482	358.8	358.8	404.7	326.5	525.7	319.2	313	13.74	0.004336	0.5232
Run 2	0.062	0.1	19.59	10482	350.4	350.4	387.8	326.1	522.7	319.2	313	16.37	0.004336	0.533
Run 3	0.074	0.1	19.34	10482	344.6	344.6	376.1	325.7	520.7	319.2	313	19.19	0.004336	0.5396
Run 4	0.086	0.1	19.17	10482	340.3	340.3	367.6	325.4	519.3	319.2	313	22.3	0.004336	0.5444
Run 5	0.098	0.1	19.05	10482	337.1	337.1	361.2	325.1	518.1	319.2	313	25.78	0.004336	0.5481
Run 6	0.11	0.1	18.95	10482	334.5	334.5	356	324.8	517.3	319.2	313	29.75	0.004336	0.551
Run 7	0.122	0.1	18.87	10482	332.5	332.5	351.9	324.6	516.5	319.2	313	34.32	0.004336	0.5533
Run 8	0.134	0.1	18.8	10482	330.8	330.8	348.5	324.3	516	319.2	313	39.68	0.004336	0.5552
Run 9	0.146	0.1	18.75	10482	329.3	329.3	345.7	324.1	515.5	319.2	313	46.05	0.004336	0.5568
Run 10	0.158	0.1	18.7	10482	328.1	328.1	343.2	323.8	515	319.2	313	53.72	0.004336	0.5581
Run 11	0.17	0.1	18.67	10482	327.1	327.1	341.1	323.6	514.7	319.2	313	63.1	0.004336	0.5593

Code for System when flow is Laminar in the solar collector, $\dot{m}$ changes, ($L = 16.2\ [m]$, $P_{Boiler} = 0.1\ [atm]$):

```
"Solar Collector"
rho_mirror=.99 "Mirror
reflectivity"
alpha_pipe=1 "Emissivity
which is equal absobility. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system. "
"At this stage we eliminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzman"
T_sun=1373 [K] "Temperature
on top of the atmosphere"
"** Physical Properties of solar collector**"
theta=70 "Angle of the
pipe to the vertical axis "
L=18.8 [m] "length of the
pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe
radias"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
epsilon_pipe=1
A_crosspipe=pi* r_1^2
"**Ambient and environmental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperature "
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=P_amb ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
viscosity in assumed condition "
k_air=conductivity(Air,T=T_avg) "Thermal
```

Coductivity in assumed condition"
alpha_air=**thermaldiffusivity**(***Air***,***T***=T_avg,***P***=P_amb) "Thermal
Diffusivity at assumed condition"
Beta_air=1/T_avg "EXPANSION
COEFFICIENT FOR AIR"

g=9.81 [m/s^2]
"**Heat from the Sun**"
Ra_L=g*Beta_air*(**cos**(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overall convection heat transfer coefficient. (Based on only natural convection)"
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4))-(h_w*A_pipe*DELTAT) "The
heat that
will conduct to the HTF"
"Q_in=2900"
"For Heat that Transfer to the HTF by conduction and convection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system "
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(**exp**((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(**exp**(373/T_avgF))-
0.000807195*(**exp**((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
h_F=3.66*k_F/D_1 "Assumed that
there is a laminar flow in the tubes"
R_Ftotal=(**ln**(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradient. That heat will calculated by following"
"m_dot=.05 [kg/s]" "HTF Mass flow rate"
Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
Q_F=Q_in
"BOILER: "
"Assume the flow in the tube is turbulent "
"Boiler has two components, Coil and boiler container. The HOT HTF flows through the coils and loss
heat and Salt water
boil by nucleate boiling "
"Coil is made by 3/8 in copper pipe"
" We assume HTF leave the boiler at the 90C temperature"
"We are going to make three equations for heat and balance them for computing all variable "
"Firs heat we are going to calculate is the heat that the HTF loss by passing through the coil in the boiler "
"Second we will calculating the heat flux that goes from the HTF by conduction to the salt water "

"Last one is the heat that which is caused increasing the inlet salt water temperature and boiling the salt water, and it is
include the heat lost through the boiler body to the environment"
"FACTS "


```
"m_dot" "It is same
amount of HTF mass flow rate in solar collector "
"COIL Features "
"L_coil=25.92*convert(ft,m)" "Coil length "
D_1coil=.375*convert(in,m) "Coil ID"
r_1coil=D_1coil/2
D_2coil=.5*convert(in,m) "Coil OD"
r_2coil=D_2coil/2
K_coil=400 [W/m*K] "Thermal
conductivity factor "
A_coil1=pi*(D_1coil^2)/4 "Coil Inner
surface area "
A_coil2=pi*(D_2coil^2)/4 "Coil Outer
surface area"
A_crosscoil=(D_1coil^2)*pi/4
P_2coil=pi*D_2coil "Outter coil
Perimeter"
A_2coilsurface=P_2coil*L_coil
" We introduce T_avgFB. this is the average of the temperature of HTF inlet and outlet.
Temperature of the oule let is assumed, T_foutB=80 C"
"T_foutB=(90+273)" "HTF outlet
temperature "
T_finB=T_Fout
T_avgFB=(T_foutB+T_finB)/2 "HTF Average
temperature in the coil"
"T_avgFB=332"
"Use Look Up Table "
mu_fb=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgFB))-
5.02057*(exp((373/T_avgFB)^2))+2.31971*exp((373/T_avgFB)^3))
nu_fb=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgFB))-
0.000807195*(exp((373/T_avgFB)^2))+0.00104979*exp((
373/T_avgFB)^3))
k_fb=1.44720528E-01+8.23925584E-05*T_avgFB-3.99012752E-07*T_avgFB^2+3.42794460E-
10*T_avgFB^3
c_pfb=1.27992524E+03+2.45018746E+00*T_avgFB+1.37430217E-03*T_avgFB^2-1.06266283E-
06*T_avgFB^3
Pr_fb=C_pfb*mu_fb/k_fb "HTF Prandtle
at T_avgFB"
Re_fb=m_dot*d_1coil/(A_crosscoil*mu_fb) "HTF Reynolds
inside the coil tube "
Nu_Dfb=.0265*(Re_fb^(4/5))*(Pr_fb^.3)
" This Nuselt is calculated for turbulent flow while it gets cool"
h_fb=Nu_Dfb*k_fb/D_1coil
"HTF
Convection heat ttransfer coefficient inside the coil tube. "
Q_fb=m_dot*C_pfb*(T_finB-T_foutB) "Energy HTF
equation "
"Conduction Heat Transfer"
"The heat flux from HTF to the outer surface of the coil tube"
"We introduce T_cbs, which is temperature on the outer surface of the coil tube"
```

```
"T_cbs=325"
R_totalFSB=((ln(r_2coil/r_1coil))/(2*pi*K_coil*L_coil))+(1/(2*pi*r_1coil*L_coil*h_fb)) "Total Thermal
```


```
resistance for HTF and coil thickness"
Q_FSB=(T_avgFB-T_cbs)/R_totalFSB "Heat flux
through convection and conduction from HTF to surface of the coil tube"
Q_fb=Q_FSB
"Nucleate Boiling heat transfer "
"We assume the heat lost is negligible because of good insulation. this heat is consist the heat which is
caused the boiling
and increasing the temperature of the inlet salt water to the saturation temperature."
"We assume the system is steady state and amount of the mass flow rate is equal to the amount of water
which is vaporized.
"
"Water Properties"
C_SF=.0128
" P_water is pressure of the boiler"
P_water= .1 [atm]
T_sat=t_sat(Water,P=(P_water*convert(atm,Pa)) )
DELTAh_vap=enthalpy_vaporization(Water,T=T_sat)
mu_fwater=viscosity(Water,T=T_sat,x=0)
v_fwater=volume(Water,T=T_sat,x=0)
cp_fwater=specheat(Water,T=T_sat,x=0)
Pr_fwater=prandtl(Water,T=T_sat,x=0)
rho_fwater=density(Water,T=T_sat,x=0)
rho_gwater=density(Water,T=T_sat,x=1)
sigma_fwater=surfacetension(Water,T=T_sat)
T_waterinlet=313
cp=cp(Water,T=T_waterinlet,x=0)
"Nucleate boiling heat per square  meter"
q_s=mu_fwater*DELTAh_vap*((g*(rho_fwater-rho_gwater)/sigma_fwater)^.5)*((cp_fwater*(T_cbs-
T_sat)/(C_SF*
DELTAh_vap*Pr_fwater))^3)
q_sReal=q_s*A_2coilsurface "Real
nucleate boiling "
m_dot_v=q_sReal/DELTAh_vap
"m_dot_v=.004336"
"The total heat that transferredto the boiler is:"
Q_SB=q_sReal+m_dot_v*cp*(T_sat-T_waterinlet)
"All Heat are equal to each other "
Q_fb=Q_SB
Q_fb=Q_F
"**Efficiency**"
Q_sun=1000*rho_mirror*A_mirror ;
    COP= m_dot_v*DELTAh_vap/Q_sun
```

Table 12: Laminar flow in the solar collector, ṁ changes (L=18.8 [m] ,P_(Boiler)=0.1 [atm], Constant)

	m	P_{water}	L	Q_{CF}	T_{avgF}	T_{avgFB}	T_{finB}	T_{cbs}	T_{osur}	T_{sat}	T_{foutB}	L_{coil}	m_v	COP
	[kg/s]	[atm]	[m]									[m]		
Run 1	0.05	0.1	18.8	7854	347.8	347.8	382.7	325.5	536.4	319.2	313	16.13	0.003249	0.4829
Run 2	0.062	0.1	18.8	8014	341.9	341.9	370.8	325.1	533.7	319.2	313	19.42	0.003315	0.4927
Run 3	0.074	0.1	18.8	8126	337.7	337.7	362.4	324.8	531.8	319.2	313	23.13	0.003362	0.4996
Run 4	0.086	0.1	18.8	8210	334.6	334.6	356.1	324.5	530.3	319.2	313	27.4	0.003396	0.5047
Run 5	0.098	0.1	18.8	8274	332.1	332.1	351.3	324.3	529.2	319.2	313	32.43	0.003423	0.5087
Run 6	0.11	0.1	18.8	8326	330.2	330.2	347.4	324	528.3	319.2	313	38.49	0.003444	0.5118
Run 7	0.122	0.1	18.8	8367	328.6	328.6	344.2	323.7	527.6	319.2	313	45.93	0.003461	0.5144
Run 8	0.134	0.1	18.8	8402	327.3	327.3	341.6	323.5	527	319.2	313	55.26	0.003476	0.5165
Run 9	0.146	0.1	18.8	8432	326.2	326.2	339.4	323.2	526.4	319.2	313	67.21	0.003488	0.5184
Run 10	0.158	0.1	18.8	8457	325.2	325.2	337.5	322.9	526	319.2	313	82.9	0.003498	0.5199
Run 11	0.17	0.1	18.8	8478	324.4	324.4	335.8	322.7	525.6	319.2	313	104.1	0.003507	0.5212

Code for System when flow is Laminar in the solar collector, P_{Boiler} changes, ($\dot{m}_V = 0.004336 \left[\frac{kg}{s}\right]$, $\dot{m} = 0.05 \left[\frac{kg}{s}\right]$):

```
"Solar Collector"
rho_mirror=.99 "Mirror
reflectivity"
alpha_pipe=1 "Emessivity
which is equal absobility. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system.”
"At this stage we eleminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzman"
T_sun=1373 [K] "Temperature
on top of the atmosphier"
"** Physical Properties of solar collecttor**"
theta=70 "Angle of the
pipe to the vertical axis "
"L=30*convert(ft,m) " "length of the
pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe
radias"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
epsilon_pipe=1
"**Ambient and enviromental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperatrue "
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=P_amb ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
viscosity in assumed condition "
k_air=conductivity(Air,T=T_avg) "Thermal
```

```
Coductivity in assumed condition"
alpha_air=thermaldiffusivity(Air,T=T_avg,P=P_amb) "Thermal
Diffusivity at assumed condition"
Beta_air=1/T_avg "EXPANSION
COEFFICIENT FOR AIR"
g=9.81 [m/s^2]

"**Heat from the Sun**"
Ra_L=g*Beta_air*(cos(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overal convection heat transfer coefficient. ( Based on only natural convection)"
"nu_wind=kinematicviscosity(Air_ha,T=T_avg,P=P_amb)
pr_wind=prandtl(Air_ha,T=T_avg,P=P_amb)
pr_Swind=prandtl(Air_ha,T=T_osur,P=P_amb)
Re_wind=6*D_2/nu_wind
C_wind=.26
m_wind=.6
n_wind=.37
NUS_wind=C_wind*(Re_wind^m_wind)*(pr_wind^n_wind)*((pr_wind/pr_Swind)^.25)
h_wind=NUS_wind*k_air/D_2
Q_wind=h_wind*A_pipe*DELTAT
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4-T_amb^4))-
(h_w*A_pipe*DELTAT)-Q_wind"
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4))-(h_w*A_pipe*DELTAT) "The
heat that
will conduct to the HTF"
"Q_in=2900"
"For Heat that Transfer to the HTF by conduction and aonvection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system "
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(exp((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgF))-
0.000807195*(exp((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
h_F=3.66*k_F/D_1 "Assumed that
there is a laminar flow in the tubes"
R_Ftotal=(ln(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradiant. That heat will calculated by following"
m_dot=.05 [kg/s] "HTF Mass flow rate"
Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
```

```
Q_F=Q_in
"BOILER: "
"Assume the flow in the tube is turbulant "
"Boiler has two componenets, Coil and boiler container. The HOT HTF flows through the coiles and loss
heat and Salt water
boil by nucleat boiling "
"Coil is made by 3/8 in copper pipe"
" We assume HTF leave the boiler at the 90C temprature"
"We are going to make three equations for heat and balance them for computing all variable "
"Firs heat we are going to calculate is the heat that the HTF loss by passing through the coil in the boiller
"
"Second we will caculating the heat flux that goes from the HTF by conduction to the salt water "
"Last one is the heat that which is caused increasing the inlet salt water temprature and boiling the salt
water, and it is
include the heat lost through the boiler body to the enviroment"
"FACTS "
"m_dot" "It is same
amount of HTF mass flow rate in solar collector "
"COIL Features "
"L_coil=25.92*convert(ft,m)" "Coil lenght "
D_1coil=.375*convert(in,m) "Coil ID"
r_1coil=D_1coil/2
D_2coil=.5*convert(in,m) "Coil OD"
r_2coil=D_2coil/2
K_coil=400 [W/m*K] "Thermal
conductivity factor "
A_coil1=pi*(D_1coil^2)/4 "Coil Inner
surface area "
A_coil2=pi*(D_2coil^2)/4 "Coil Outer
surface area"
A_crosscoil=(D_1coil^2)*pi/4
P_2coil=pi*D_2coil "Outter coil
Perimeter"
A_2coilsurface=P_2coil*L_coil
" We introduce T_avgFB. this is the average of the temprature of HTF inlet and oulet.
Temperature of the oule let is assumed, T_foutB=80 C"
"T_foutB=(90+273)" "HTF outlet
temperature "
T_finB=T_Fout
T_avgFB=(T_foutB+T_finB)/2 "HTF Average
temperature in the coil"
"T_avgFB=332"
"Use Look Up Table "
mu_fb=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgFB))-
5.02057*(exp((373/T_avgFB)^2))+2.31971*exp((373/T_avgFB)^3))
nu_fb=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgFB))-
0.000807195*(exp((373/T_avgFB)^2))+0.00104979*exp((
373/T_avgFB)^3))
k_fb=1.44720528E-01+8.23925584E-05*T_avgFB-3.99012752E-07*T_avgFB^2+3.42794460E-
10*T_avgFB^3
c_pfb=1.27992524E+03+2.45018746E+00*T_avgFB+1.37430217E-03*T_avgFB^2-1.06266283E-
06*T_avgFB^3
Pr_fb=C_pfb*mu_fb/k_fb "HTF Prandtle
at T_avgFB"
Re_fb=m_dot*d_1coil/(A_crosscoil*mu_fb) "HTF Renoulds
inside the coil tube "
```

```
Nu_Dfb=.0265*(Re_fb^(4/5))*(Pr_fb^.3)
" This Nuselt is calculated for turbolent flow while it gets cool"
h_fb=Nu_Dfb*k_fb/D_1coil
"HTF
Convection heat ttransfer coefficient inside the coil tube. "
Q_fb=m_dot*C_pfb*(T_finB-T_foutB) "Energy HTF
equation "
"Conduction Heat Transfer"
"The heat fulx from HTF to the outer surface of the coil tube"
"We introduce T_cbs, which is teperature on the outer surface of the coil tube"
"T_cbs=325"
R_totalFSB=((ln(r_2coil/r_1coil))/(2*pi*K_coil*L_coil))+(1/(2*pi*r_1coil*L_coil*h_fb)) "Total Thermal
resistance for HTF and coil thickness"
Q_FSB=(T_avgFB-T_cbs)/R_totalFSB "Heat flux
through convection and conduction from HTF to surface of the coil tube"
Q_fb=Q_FSB
"Nucleate Boiling heat transfer "
"We assume the heat lost is negligible because of good insulation. this heat is consist the heat which is
caused the boiling
and increasing the temprature of the inlet salt water to the saturation temperature."
"We assume the system is steady state and amount of the mass flow rate is equal to the amount of water
which is vaporized.
"
"Water Properties"
C_SF=.0128
" P_water is pressure of the boiler"
T_sat=t_sat(Water,P=(P_water*convert(atm,Pa)) )
DELTAh_vap=enthalpy_vaporization(Water,T=T_sat)
mu_fwater=viscosity(Water,T=T_sat,x=0)
v_fwater=volume(Water,T=T_sat,x=0)
cp_fwater=specheat(Water,T=T_sat,x=0)
Pr_fwater=prandtl(Water,T=T_sat,x=0)
rho_fwater=density(Water,T=T_sat,x=0)
rho_gwater=density(Water,T=T_sat,x=1)
sigma_fwater=surfacetension(Water,T=T_sat)
T_waterinlet=313
cp=cp(Water,T=T_waterinlet,x=0)
"Nucleate boiling heat per squar meter"
q_s=mu_fwater*DELTAh_vap*((g*(rho_fwater-rho_gwater)/sigma_fwater)^.5)*((cp_fwater*(T_cbs-
T_sat)/(C_SF*
DELTAh_vap*Pr_fwater))^3)
q_sReal=q_s*A_2coilsurface "Real
nucleate boiling "
m_dot_v=q_sReal/DELTAh_vap
m_dot_v=.004336
"The total heat that transferredto the boiler is:"
Q_SB=q_sReal+m_dot_v*cp*(T_sat-T_waterinlet)
"All Heat are equal to each other "
Q_fb=Q_SB
Q_fb=Q_F
"**Efficiency**"
Q_sun=1000*rho_mirror*A_mirror
COP= m_dot_v*DELTAh_vap/Q_sun
```

Table 13: Laminar flow in the solar collector, P_(Boiler)changes, (ṁ _V=0.004336 [kg/s],ṁ =0.05 [kg/s], Constant):

	P_{water}	m	m_v	L	Q_{CF}	T_{avgF}	T_{avgFB}	T_{finB}	T_{cbs}	T_{osur}	T_{sat}	T_{foutB}	L_{coil}	COP
		[kg/s]		[m]									[m]	
Run 1	0.05	0.05	0.004336	19.81	10381	358.4	358.4	403.8	313.8	526	306.3	313	9.909	0.5338
Run 2	0.1	0.05	0.004336	19.95	10482	358.8	358.8	404.7	326.5	525.7	319.2	313	13.74	0.5232
Run 3	0.15	0.05	0.004336	20.04	10544	359.1	359.1	405.2	334.3	525.4	327.4	313	17.99	0.5166
Run 4	0.2	0.05	0.004336	20.11	10591	359.3	359.3	405.6	340	525.3	333.5	313	23.18	0.5117
Run 5	0.25	0.05	0.004336	20.16	10628	359.4	359.4	405.9	344.1	525.2	338.4	313	29.26	0.5077
Run 6	0.3	0.05	0.004336	20.2	10659	359.6	359.6	406.1	347.5	525	342.6	313	37.4	0.5044
Run 7	0.35	0.05	0.004336	20.24	10685	359.7	359.7	406.3	350.5	525	346.2	313	49.18	0.5015
Run 8	0.4	0.05	0.004336	20.28	10709	359.8	359.8	406.5	353.1	524.9	349.3	313	67.83	0.499
Run 9	0.45	0.05	0.004336	20.31	10729	359.9	359.9	406.7	355.4	524.8	352.2	313	101.5	0.4967
Run 10	0.5	0.05	0.004336	20.33	10748	359.9	359.9	406.9	357.4	524.8	354.8	313	178.2	0.4947
Run 11	0.55	0.05	0.004336	20.36	10765	360	360	407	359	524.7	357.2	313	468.6	0.4928

Code for System when flow is Laminar in the solar collector, P_{Boiler} changes, ($L = 17\ [m]$, $\dot{m} = 0.05\ \left[\frac{kg}{s}\right]$):

```
"Solar Collector"
rho_mirror=.99 "Mirror
reflectivity"
alpha_pipe=1 "Emessivity
which is equal absobility. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system. "
"At this stage we eleminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzman"
T_sun=1373 [K] "Temperature
on top of the atmosphier"
"** Physical Properties of solar collecttor**"
theta=70 "Angle of the
pipe to the vertical axis "
L=17 [m]
"length of the pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe
radias"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
epsilon_pipe=1
"**Ambient and enviromental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperatrue "
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=P_amb ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
viscosity in assumed condition "
k_air=conductivity(Air,T=T_avg) "Thermal
Coductivity in assumed condition"
```

```
alpha_air=thermaldiffusivity(Air,T=T_avg,P=P_amb) "Thermal
Diffusivity at assumed condition"
Beta_air=1/T_avg "EXPANSION
COEFFICIENT FOR AIR"
g=9.81 [m/s^2]
File:Solar collector-Boiller-constant solar collector length.EES 8/30/2017 6:07:56 PM Page 2
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"**Heat from the Sun**"
Ra_L=g*Beta_air*(cos(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overal convection heat transfer coefficient. ( Based on only natural convection)"
"nu_wind=kinematicviscosity(Air_ha,T=T_avg,P=P_amb)
pr_wind=prandtl(Air_ha,T=T_avg,P=P_amb)
pr_Swind=prandtl(Air_ha,T=T_osur,P=P_amb)
Re_wind=6*D_2/nu_wind
C_wind=.26
m_wind=.6
n_wind=.37
NUS_wind=C_wind*(Re_wind^m_wind)*(pr_wind^n_wind)*((pr_wind/pr_Swind)^.25)
h_wind=NUS_wind*k_air/D_2
Q_wind=h_wind*A_pipe*DELTAT
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4-T_amb^4))-
(h_w*A_pipe*DELTAT)-Q_wind"
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4))-(h_w*A_pipe*DELTAT) "The
heat that
will conduct to the HTF"
"For Heat that Transfer to the HTF by conduction and aonvection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system "
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(exp((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgF))-
0.000807195*(exp((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
h_F=3.66*k_F/D_1 "Assumed that
there is a laminar flow in the tubes"
R_Ftotal=(ln(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradiant. That heat will calculated by following"
m_dot=.05 [kg/s] "HTF Mass flow rate"
Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
Q_F=Q_in
```

"BOILER: "


```
"Assume the flow in the tube is turbulant "
"Boiler has two componenets, Coil and boiler container. The HOT HTF flows through the coiles and loss
heat and Salt water
boil by nucleat boiling "
"Coil is made by 3/8 in copper pipe"
" We assume HTF leave the boiler at the 90C temprature"
"We are going to make three equations for heat and balance them for computing all variable "
"Firs heat we are going to calculate is the heat that the HTF loss by passing through the coil in the boiller
"
"Second we will caculating the heat flux that goes from the HTF by conduction to the salt water "
"Last one is the heat that which is caused increasing the inlet salt water temprature and boiling the salt
water, and it is
include the heat lost through the boiler body to the enviroment"
"FACTS "
"m_dot" "It is same
amount of HTF mass flow rate in solar collector "
"COIL Features "
"L_coil=25.92*convert(ft,m)" "Coil lenght "
D_1coil=.375*convert(in,m) "Coil ID"
r_1coil=D_1coil/2
D_2coil=.5*convert(in,m) "Coil OD"
r_2coil=D_2coil/2
K_coil=400 [W/m*K] "Thermal
conductivity factor "
A_coil1=pi*(D_1coil^2)/4 "Coil Inner
surface area "
A_coil2=pi*(D_2coil^2)/4 "Coil Outer
surface area"
A_crosscoil=(D_1coil^2)*pi/4
P_2coil=pi*D_2coil "Outter coil
Perimeter"
A_2coilsurface=P_2coil*L_coil
" We introduce T_avgFB. this is the average of the temprature of HTF inlet and oulet.
Temperature of the oule let is assumed, T_foutB=80 C"
"T_foutB=(90+273)" "HTF outlet
temperature "
T_finB=T_Fout
T_avgFB=(T_foutB+T_finB)/2 "HTF Average
temperature in the coil"
"T_avgFB=332"
"Use Look Up Table "
mu_fb=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgFB))-
5.02057*(exp((373/T_avgFB)^2))+2.31971*exp((373/T_avgFB)^3))
nu_fb=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgFB))-
0.000807195*(exp((373/T_avgFB)^2))+0.00104979*exp((
373/T_avgFB)^3))
k_fb=1.44720528E-01+8.23925584E-05*T_avgFB-3.99012752E-07*T_avgFB^2+3.42794460E-
10*T_avgFB^3
c_pfb=1.27992524E+03+2.45018746E+00*T_avgFB+1.37430217E-03*T_avgFB^2-1.06266283E-
06*T_avgFB^3
Pr_fb=C_pfb*mu_fb/k_fb "HTF Prandtle
at T_avgFB"
Re_fb=m_dot*d_1coil/(A_crosscoil*mu_fb) "HTF Renoulds
```

```
inside the coil tube "
Nu_Dfb=.0265*(Re_fb^(4/5))*(Pr_fb^.3)
" This Nuselt is calculated for turbolent flow while it gets cool"
```

```
h_fb=Nu_Dfb*k_fb/D_1coil
"HTF
Convection heat ttransfer coefficient inside the coil tube. "
Q_fb=m_dot*C_pfb*(T_finB-T_foutB) "Energy HTF
equation "
"Conduction Heat Transfer"
"The heat fulx from HTF to the outer surface of the coil tube"
"We introduce T_cbs, which is teperature on the outer surface of the coil tube"
"T_cbs=325"
R_totalFSB=((ln(r_2coil/r_1coil))/(2*pi*K_coil*L_coil))+(1/(2*pi*r_1coil*L_coil*h_fb)) "Total Thermal
resistance for HTF and coil thickness"
Q_FSB=(T_avgFB-T_cbs)/R_totalFSB "Heat flux
through convection and conduction from HTF to surface of the coil tube"
Q_fb=Q_FSB
"Nucleate Boiling heat transfer "
"We assume the heat lost is negligible because of good insulation. this heat is consist the heat which is
caused the boiling
and increasing the temprature of the inlet salt water to the saturation temperature."
"We assume the system is steady state and amount of the mass flow rate is equal to the amount of water
which is vaporized.
"
"Water Properties"
C_SF=.0128
" P_water is pressure of the boiler"
T_sat=t_sat(Water,P=(P_water*convert(atm,Pa)) )
DELTAh_vap=enthalpy_vaporization(Water,T=T_sat)
mu_fwater=viscosity(Water,T=T_sat,x=0)
v_fwater=volume(Water,T=T_sat,x=0)
cp_fwater=specheat(Water,T=T_sat,x=0)
Pr_fwater=prandtl(Water,T=T_sat,x=0)
rho_fwater=density(Water,T=T_sat,x=0)
rho_gwater=density(Water,T=T_sat,x=1)
sigma_fwater=surfacetension(Water,T=T_sat)
T_waterinlet=313
cp=cp(Water,T=T_waterinlet,x=0)
"Nucleate boiling heat per squar meter"
q_s=mu_fwater*DELTAh_vap*((g*(rho_fwater-rho_gwater)/sigma_fwater)^.5)*((cp_fwater*(T_cbs-
T_sat)/(C_SF*
DELTAh_vap*Pr_fwater))^3)
q_sReal=q_s*A_2coilsurface "Real
nucleate boiling "
m_dot_v=q_sReal/DELTAh_vap
"m_dot_v=.004336"
"The total heat that transferredto the boiler is:"
Q_SB=q_sReal+m_dot_v*cp*(T_sat-T_waterinlet)
"All Heat are equal to each other "
Q_fb=Q_SB
Q_fb=Q_F
"**Efficiency**"
Q_sun=1000*rho_mirror*A_mirror
COP= m_dot_v*DELTAh_vap/Q_sun
```

Table 14: Laminar flow in the solar collector, P_(Boiler)changes, (L=17 [m] ,m˙ =0.05 [kg/s], Constant)

	P_{water}	m	m_v	L	Q_{CF}	T_{avgF}	T_{avgFB}	T_{finB}	T_{cbs}	T_{osur}	T_{sat}	T_{foutB}	L_{coil}	COP
		[kg/s]		[m]									[m]	
Run 1	0.05	0.05	0.003514	17	8412	350.2	350.2	387.4	313.2	533.8	306.3	313	10.27	0.504
Run 2	0.085	0.05	0.003488	17	8412	350.2	350.2	387.4	322.7	533.8	316.1	313	13.81	0.4955
Run 3	0.12	0.05	0.003471	17	8412	350.2	350.2	387.4	329.1	533.8	322.8	313	17.99	0.4897
Run 4	0.155	0.05	0.003457	17	8412	350.2	350.2	387.4	333.9	533.8	328.1	313	23.34	0.4852
Run 5	0.19	0.05	0.003447	17	8412	350.2	350.2	387.4	337.8	533.8	332.4	313	30.66	0.4816
Run 6	0.225	0.05	0.003438	17	8412	350.2	350.2	387.4	340.9	533.8	336.1	313	40.84	0.4785
Run 7	0.26	0.05	0.00343	17	8412	350.2	350.2	387.4	343.5	533.8	339.3	313	56.35	0.4758
Run 8	0.295	0.05	0.003423	17	8412	350.2	350.2	387.4	345.7	533.8	342.2	313	84.17	0.4734
Run 9	0.33	0.05	0.003417	17	8412	350.2	350.2	387.4	347.6	533.8	344.8	313	146.4	0.4713
Run 10	0.365	0.05	0.003411	17	8412	350.2	350.2	387.4	349.2	533.8	347.2	313	369.4	0.4693
Run 11	0.4	0.05	0.003406	17	8412	350.2	350.2	387.4	350.1	533.8	349.3	313	5663	0.4675

Code for System when the flow is Turbulent in the solar collector, P_{Boiler} changes, ($\dot{m}_V = 0.004336 \left[\frac{kg}{s}\right]$, $\dot{m} = 0.1708 \left[\frac{kg}{s}\right]$):

```
"Solar Collector"
rho_mirror=.99 "Mirror
reflectivity"
alpha_pipe=1 "Emessivity
which is equal absobility. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system. "
"At this stage we eleminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzman"
T_sun=1373 [K] "Temperature
on top of the atmosphier"
"** Physical Properties of solar collecttor**"
theta=70 "Angle of the
pipe to the vertical axis "
"L=30*convert(ft,m) " "length of the
pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe
radias"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
A_crosspipe=pi*r_1^2
epsilon_pipe=1
"**Ambient and enviromental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperatrue”
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=P_amb ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
viscosity in assumed condition "
k_air=conductivity(Air,T=T_avg) "Thermal
```

```
Coductivity in assumed condition"
alpha_air=thermaldiffusivity(Air,T=T_avg,P=P_amb) "Thermal
Diffusivity at assumed condition"
Beta_air=1/T_avg "EXPANSION
COEFFICIENT FOR AIR"
g=9.81 [m/s^2]
"**Heat from the Sun**"
Ra_L=g*Beta_air*(cos(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overal convection heat transfer coefficient. ( Based on only natural convection)"
"nu_wind=kinematicviscosity(Air_ha,T=T_avg,P=P_amb)
pr_wind=prandtl(Air_ha,T=T_avg,P=P_amb)
pr_Swind=prandtl(Air_ha,T=T_osur,P=P_amb)
Re_wind=6*D_2/nu_wind
C_wind=.26
m_wind=.6
n_wind=.37
NUS_wind=C_wind*(Re_wind^m_wind)*(pr_wind^n_wind)*((pr_wind/pr_Swind)^.25)
h_wind=NUS_wind*k_air/D_2
Q_wind=h_wind*A_pipe*DELTAT
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4-T_amb^4))-
(h_w*A_pipe*DELTAT)-Q_wind"
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4))-(h_w*A_pipe*DELTAT) "The
heat that
will conduct to the HTF"
"Q_in=2900"
"For Heat that Transfer to the HTF by conduction and aonvection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system "
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(exp((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgF))-
0.000807195*(exp((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
m_dot=.1766 [kg/s] "HTF Mass flow rate"
Re_F= m_dot*D_1/(A_crosspipe*mu_f)
Pr_F= C_PF*mu_f/k_F
NU_F1=.0263*(Re_F^(3/4)) *(Pr_F^.4)
h_F=NU_F1*k_F/D_1
R_Ftotal=(ln(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradiant. That heat will calculated by following"
```

```
"m_dot=.05 [kg/s]" "HTF Mass flow rate"
Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
Q_F=Q_in
"BOILER: "
"Assume the flow in the tube is turbulant "
"Boiler has two componenets, Coil and boiler container. The HOT HTF flows through the coiles and loss heat and Salt water
boil by nucleat boiling "
"Coil is made by 3/8 in copper pipe"
" We assume HTF leave the boiler at the 90C temprature"
"We are going to make three equations for heat and balance them for computing all variable "
"Firs heat we are going to calculate is the heat that the HTF loss by passing through the coil in the boiller
"
"Second we will caculating the heat flux that goes from the HTF by conduction to the salt water "
"Last one is the heat that which is caused increasing the inlet salt water temprature and boiling the salt water, and it is
include the heat lost through the boiler body to the enviroment"
"FACTS "
"m_dot" "It is same
amount of HTF mass flow rate in solar collector "
"COIL Features "
"L_coil=25.92*convert(ft,m)" "Coil lenght "
D_1coil=.375*convert(in,m) "Coil ID"
r_1coil=D_1coil/2
D_2coil=.5*convert(in,m) "Coil OD"
r_2coil=D_2coil/2
K_coil=400 [W/m*K] "Thermal
conductivity factor "
A_coil1=pi*(D_1coil^2)/4 "Coil Inner
surface area "
A_coil2=pi*(D_2coil^2)/4 "Coil Outer
surface area"
A_crosscoil=(D_1coil^2)*pi/4
P_2coil=pi*D_2coil "Outter coil
Perimeter"
A_2coilsurface=P_2coil*L_coil
" We introduce T_avgFB. this is the average of the temprature of HTF inlet and oulet.
Temperature of the oule let is assumed, T_foutB=80 C"
"T_foutB=(90+273)" "HTF outlet
temperature "
T_finB=T_Fout
T_avgFB=(T_foutB+T_finB)/2 "HTF Average
temperature in the coil"
"T_avgFB=332"
"Use Look Up Table "
mu_fb=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgFB))-
5.02057*(exp((373/T_avgFB)^2))+2.31971*exp((373/T_avgFB)^3))
nu_fb=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgFB))-
0.000807195*(exp((373/T_avgFB)^2))+0.00104979*exp((
373/T_avgFB)^3))
k_fb=1.44720528E-01+8.23925584E-05*T_avgFB-3.99012752E-07*T_avgFB^2+3.42794460E-
10*T_avgFB^3
c_pfb=1.27992524E+03+2.45018746E+00*T_avgFB+1.37430217E-03*T_avgFB^2-1.06266283E-
06*T_avgFB^3
Pr_fb=C_pfb*mu_fb/k_fb "HTF Prandtle
at T_avgFB"
```

```
Re_fb=m_dot*d_1coil/(A_crosscoil*mu_fb) "HTF Renoulds
inside the coil tube "
Nu_Dfb=.0265*(Re_fb^(4/5))*(Pr_fb^.3)
" This Nuselt is calculated for turbolent flow while it gets cool"
h_fb=Nu_Dfb*k_fb/D_1coil
"HTF
Convection heat ttransfer coefficient inside the coil tube. "
Q_fb=m_dot*C_pfb*(T_finB-T_foutB) "Energy HTF
equation "
"Conduction Heat Transfer"
"The heat fulx from HTF to the outer surface of the coil tube"
"We introduce T_cbs, which is teperature on the outer surface of the coil tube"
"T_cbs=325"
R_totalFSB=((ln(r_2coil/r_1coil))/(2*pi*K_coil*L_coil))+(1/(2*pi*r_1coil*L_coil*h_fb)) "Total Thermal
resistance for HTF and coil thickness"
Q_FSB=(T_avgFB-T_cbs)/R_totalFSB "Heat flux
through convection and conduction from HTF to surface of the coil tube"
Q_fb=Q_FSB
"Nucleate Boiling heat transfer "
"We assume the heat lost is negligible because of good insulation. this heat is consist the heat which is
caused the boiling
and increasing the temprature of the inlet salt water to the saturation temperature."
"We assume the system is steady state and amount of the mass flow rate is equal to the amount of water
which is vaporized.
"
"Water Properties"
C_SF=.0128
" P_water is pressure of the boiler"
T_sat=t_sat(Water,P=(P_water*convert(atm,Pa)) )
DELTAh_vap=enthalpy_vaporization(Water,T=T_sat)
mu_fwater=viscosity(Water,T=T_sat,x=0)
v_fwater=volume(Water,T=T_sat,x=0)
cp_fwater=specheat(Water,T=T_sat,x=0)
Pr_fwater=prandtl(Water,T=T_sat,x=0)
rho_fwater=density(Water,T=T_sat,x=0)
rho_gwater=density(Water,T=T_sat,x=1)
sigma_fwater=surfacetension(Water,T=T_sat)
T_waterinlet=313
cp=cp(Water,T=T_waterinlet,x=0)
"Nucleate boiling heat per squar meter"
q_s=mu_fwater*DELTAh_vap*((g*(rho_fwater-rho_gwater)/sigma_fwater)^.5)*((cp_fwater*(T_cbs-
T_sat)/(C_SF*
DELTAh_vap*Pr_fwater))^3)
q_sReal=q_s*A_2coilsurface "Real
nucleate boiling "
m_dot_v=q_sReal/DELTAh_vap
m_dot_v=.004336
"The total heat that transferredto the boiler is:"
Q_SB=q_sReal+m_dot_v*cp*(T_sat-T_waterinlet)
"All Heat are equal to each other "
```

```
Q_fb=Q_SB
Q_fb=Q_F
"**Efficiency**"
Q_sun=1000*rho_mirror*A_mirror
COP= m_dot_v*DELTAh_vap/Q_sun
```

Table 15: Turbulent flow in the solar collector, P_(Boiler)changes, (ṁ_V=0.004336 [kg/s],ṁ=0.1766 [kg/s], Constant):

	P_{water}	m [kg/s]	m_v	L [m]	Q_{CF}	T_{avgF}	T_{avgFB}	T_{finB}	T_{cbs}	T_{osur}	T_{sat}	T_{foutB}	L_{coil} [m]	COP
Run 1	0.05	0.1767	0.004336	11.7	10381	326.4	326.4	339.8	312.8	361.6	306.3	313	15.59	0.9034
Run 2	0.059	0.1767	0.004336	11.73	10404	326.4	326.4	339.9	315.4	361.5	309.3	313	19.31	0.8988
Run 3	0.068	0.1767	0.004336	11.75	10425	326.5	326.5	339.9	317.7	361.5	311.9	313	24.21	0.8948
Run 4	0.077	0.1767	0.004336	11.77	10443	326.5	326.5	340	319.6	361.4	314.2	313	30.96	0.8913
Run 5	0.086	0.1767	0.004336	11.79	10459	326.5	326.5	340	321.3	361.4	316.3	313	40.82	0.8881
Run 6	0.095	0.1767	0.004336	11.81	10474	326.5	326.5	340.1	322.7	361.4	318.2	313	56.32	0.8851
Run 7	0.104	0.1767	0.004336	11.82	10488	326.6	326.6	340.1	324	361.3	320	313	83.43	0.8824
Run 8	0.113	0.1767	0.004336	11.83	10500	326.6	326.6	340.1	325	361.3	321.6	313	139.2	0.88
Run 9	0.122	0.1767	0.004336	11.85	10512	326.6	326.6	340.2	325.8	361.3	323.2	313	290.5	0.8776
Run 10	0.131	0.1767	0.004336	11.86	10523	326.6	326.6	340.2	326.4	361.3	324.6	313	1017	0.8755
Run 11	0.14	0.1767	0.004336	11.87	10534	326.6	326.6	340.2	326.6	361.2	326	313	23664	0.8734

Code for System when the flow is Turbulent in the solar collector, P_{Boiler} changes, ($L = 17[m]$, $\dot{m} = 0.1708\ \left[\frac{kg}{s}\right]$):

```
"Solar Collector"
rho_mirror=.99 "Mirror
reflectivity"
alpha_pipe=1 "Emessivity
which is equal absobility. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system. "
"At this stage we eleminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzman"
T_sun=1373 [K] "Temperature
on top of the atmosphier"
"** Physical Properties of solar collecttor**"
theta=70 "Angle of the
pipe to the vertical axis "
L=17 [m]
"length of the pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe
radias"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
epsilon_pipe=1
A_crosspipe=pi*r_1^2
"**Ambient and enviromental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperatrue"
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=P_amb ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
viscosity in assumed condition "
k_air=conductivity(Air,T=T_avg) "Thermal
```

```
Coductivity in assumed condition"
alpha_air=thermaldiffusivity(Air,T=T_avg,P=P_amb) "Thermal
Diffusivity at assumed condition"
Beta_air=1/T_avg "EXPANSION
COEFFICIENT FOR AIR"
g=9.81 [m/s^2]
"**Heat from the Sun**"
Ra_L=g*Beta_air*(cos(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overal convection heat transfer coefficient. ( Based on only natural convection)"
"nu_wind=kinematicviscosity(Air_ha,T=T_avg,P=P_amb)
pr_wind=prandtl(Air_ha,T=T_avg,P=P_amb)
pr_Swind=prandtl(Air_ha,T=T_osur,P=P_amb)
Re_wind=6*D_2/nu_wind
C_wind=.26
m_wind=.6
n_wind=.37
NUS_wind=C_wind*(Re_wind^m_wind)*(pr_wind^n_wind)*((pr_wind/pr_Swind)^.25)
h_wind=NUS_wind*k_air/D_2
Q_wind=h_wind*A_pipe*DELTAT
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4-T_amb^4))-
(h_w*A_pipe*DELTAT)-Q_wind"
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4))-(h_w*A_pipe*DELTAT) "The
heat that
will conduct to the HTF"
"Q_in=2900"
"For Heat that Transfer to the HTF by conduction and aonvection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system "
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(exp((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgF))-
0.000807195*(exp((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
m_dot=.1766 [kg/s] "HTF Mass flow rate"
Re_F= m_dot*D_1/(A_crosspipe*mu_f)
Pr_F= C_PF*mu_f/k_F
NU_F1=.0263*(Re_F^(3/4)) *(Pr_F^.4)
h_F=NU_F1*k_F/D_1
R_Ftotal=(ln(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradiant. That heat will calculated by following"
```

```
"m_dot=.05 [kg/s]" "HTF Mass flow rate"
Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
Q_F=Q_in
"BOILER: "
"Assume the flow in the tube is turbulant "
"Boiler has two componenets, Coil and boiler container. The HOT HTF flows through the coiles and loss
heat and Salt water
boil by nucleat boiling "
"Coil is made by 3/8 in copper pipe"
" We assume HTF leave the boiler at the 90C temprature"
"We are going to make three equations for heat and balance them for computing all variable "
"Firs heat we are going to calculate is the heat that the HTF loss by passing through the coil in the boiller
"
"Second we will caculating the heat flux that goes from the HTF by conduction to the salt water "
"Last one is the heat that which is caused increasing the inlet salt water temprature and boiling the salt
water, and it is
include the heat lost through the boiler body to the enviroment"
"FACTS "
"m_dot" "It is same
amount of HTF mass flow rate in solar collector "
"COIL Features "
"L_coil=25.92*convert(ft,m)" "Coil lenght "
D_1coil=.375*convert(in,m) "Coil ID"
r_1coil=D_1coil/2
D_2coil=.5*convert(in,m) "Coil OD"
r_2coil=D_2coil/2
K_coil=400 [W/m*K] "Thermal
conductivity factor "
A_coil1=pi*(D_1coil^2)/4 "Coil Inner
surface area "
A_coil2=pi*(D_2coil^2)/4 "Coil Outer
surface area"
A_crosscoil=(D_1coil^2)*pi/4
P_2coil=pi*D_2coil "Outter coil
Perimeter"
A_2coilsurface=P_2coil*L_coil
" We introduce T_avgFB. this is the average of the temprature of HTF inlet and oulet.
Temperature of the oule let is assumed, T_foutB=80 C"
"T_foutB=(90+273)" "HTF outlet
temperature "
T_finB=T_Fout
T_avgFB=(T_foutB+T_finB)/2 "HTF Average
temperature in the coil"
"T_avgFB=332"
"Use Look Up Table "
mu_fb=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgFB))-
5.02057*(exp((373/T_avgFB)^2))+2.31971*exp((373/T_avgFB)^3))
nu_fb=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgFB))-
0.000807195*(exp((373/T_avgFB)^2))+0.00104979*exp((
373/T_avgFB)^3))
k_fb=1.44720528E-01+8.23925584E-05*T_avgFB-3.99012752E-07*T_avgFB^2+3.42794460E-
10*T_avgFB^3
c_pfb=1.27992524E+03+2.45018746E+00*T_avgFB+1.37430217E-03*T_avgFB^2-1.06266283E-
06*T_avgFB^3
Pr_fb=C_pfb*mu_fb/k_fb "HTF Prandtle
at T_avgFB"
```

```
Re_fb=m_dot*d_1coil/(A_crosscoil*mu_fb) "HTF Renoulds
inside the coil tube "
Nu_Dfb=.0265*(Re_fb^(4/5))*(Pr_fb^.3)
" This Nuselt is calculated for turbolent flow while it gets cool"
h_fb=Nu_Dfb*k_fb/D_1coil
"HTF
Convection heat ttransfer coefficient inside the coil tube. "
Q_fb=m_dot*C_pfb*(T_finB-T_foutB) "Energy HTF
equation "
"Conduction Heat Transfer"
"The heat fulx from HTF to the outer surface of the coil tube"
"We introduce T_cbs, which is teperature on the outer surface of the coil tube"
"T_cbs=325"
R_totalFSB=((ln(r_2coil/r_1coil))/(2*pi*K_coil*L_coil))+(1/(2*pi*r_1coil*L_coil*h_fb)) "Total Thermal
resistance for HTF and coil thickness"
Q_FSB=(T_avgFB-T_cbs)/R_totalFSB "Heat flux
through convection and conduction from HTF to surface of the coil tube"
Q_fb=Q_FSB
"Nucleate Boiling heat transfer "
"We assume the heat lost is negligible because of good insulation. this heat is consist the heat which is
caused the boiling
and increasing the temprature of the inlet salt water to the saturation temperature."
"We assume the system is steady state and amount of the mass flow rate is equal to the amount of water
which is vaporized.
"
"Water Properties"
C_SF=.0128
" P_water is pressure of the boiler"
T_sat=t_sat(Water,P=(P_water*convert(atm,Pa)) )
DELTAh_vap=enthalpy_vaporization(Water,T=T_sat)
mu_fwater=viscosity(Water,T=T_sat,x=0)
v_fwater=volume(Water,T=T_sat,x=0)
cp_fwater=specheat(Water,T=T_sat,x=0)
Pr_fwater=prandtl(Water,T=T_sat,x=0)
rho_fwater=density(Water,T=T_sat,x=0)
rho_gwater=density(Water,T=T_sat,x=1)
sigma_fwater=surfacetension(Water,T=T_sat)
T_waterinlet=313
cp=cp(Water,T=T_waterinlet,x=0)
"Nucleate boiling heat per squar meter"
q_s=mu_fwater*DELTAh_vap*((g*(rho_fwater-rho_gwater)/sigma_fwater)^.5)*((cp_fwater*(T_cbs-
T_sat)/(C_SF*
DELTAh_vap*Pr_fwater))^3)
q_sReal=q_s*A_2coilsurface "Real
nucleate boiling "
m_dot_v=q_sReal/DELTAh_vap
"m_dot_v=.004336"
"The total heat that transferredto the boiler is:"
Q_SB=q_sReal+m_dot_v*cp*(T_sat-T_waterinlet)
"All Heat are equal to each other "
Q_fb=Q_SB
Q_fb=Q_F
"**Efficiency**"
Q_sun=1000*rho_mirror*A_mirror
COP= m_dot_v*DELTAh_vap/Q_sun
```

Table 16 Turbulent flow in the solar collector, P_ (Boiler) changes, (L=17[m], ṁ =0.1766 [kg/s], Constant):

	P_{water}	m [kg/s]	m_v	L [m]	Q_{CF}	T_{avgF}	T_{avgFB}	T_{finB}	T_{cbs}	T_{osur}	T_{sat}	T_{foutB}	L_{coil} [m]	COP
Run 1	0.05	0.1767	0.006353	17	15211	332.5	332.5	352	313.7	355.8	306.3	313	15.55	0.9114
Run 2	0.064	0.1767	0.006332	17	15211	332.5	332.5	352	317.7	355.8	310.7	313	19.82	0.9044
Run 3	0.078	0.1767	0.006315	17	15211	332.5	332.5	352	321	355.8	314.4	313	25.42	0.8986
Run 4	0.092	0.1767	0.0063	17	15211	332.5	332.5	352	323.7	355.8	317.6	313	33.17	0.8936
Run 5	0.106	0.1767	0.006287	17	15211	332.5	332.5	352	325.9	355.8	320.4	313	44.63	0.8893
Run 6	0.12	0.1767	0.006276	17	15211	332.5	332.5	352	327.9	355.8	322.8	313	63.07	0.8855
Run 7	0.134	0.1767	0.006265	17	15211	332.5	332.5	352	329.5	355.8	325.1	313	96.61	0.8821
Run 8	0.148	0.1767	0.006256	17	15211	332.5	332.5	352	330.8	355.8	327.1	313	170.7	0.8789
Run 9	0.162	0.1767	0.006248	17	15211	332.5	332.5	352	331.8	355.8	329	313	404.6	0.876
Run 10	0.176	0.1767	0.00624	17	15211	332.5	332.5	352	332.4	355.8	330.8	313	2135	0.8734

Code for System when the flow is Turbulent in the solar collector, $\dot{m}$ changes, ($\dot{m}_V = 0.004336 \left[\frac{kg}{s}\right]$, $P_{Boiler} = 0.1\ [atm]$):

```
"Solar Collector"
rho_mirror=.99 "Mirror
reflectivity"
alpha_pipe=1 "Emessivity
which is equal absobility. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system. "
"At this stage we eleminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzman"
T_sun=1373 [K] "Temperature
on top of the atmosphier"
"** Physical Properties of solar collecttor**"
theta=70 "Angle of the
pipe to the vertical axis "
"L=30*convert(ft,m) " "length of the
pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe
radias"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
epsilon_pipe=1
A_crosspipe= pi*r_1^2
"**Ambient and enviromental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperatrue "
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=P_amb ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
```

```
viscosity in assumed condition "
k_air=conductivity(Air,T=T_avg) "Thermal
Coductivity in assumed condition"
alpha_air=thermaldiffusivity(Air,T=T_avg,P=P_amb) "Thermal
Diffusivity at assumed condition"
Beta_air=1/T_avg "EXPANSION
COEFFICIENT FOR AIR"
```



```
g=9.81 [m/s^2]
"**Heat from the Sun**"
Ra_L=g*Beta_air*(cos(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overal convection heat transfer coefficient. ( Based on only natural convection)"
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4))-(h_w*A_pipe*DELTAT) "The
heat that
will conduct to the HTF"
"Q_in=2900"
"For Heat that Transfer to the HTF by conduction and aonvection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system "
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(exp((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgF))-
0.000807195*(exp((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
" m_dot=.1766 [kg/s]" "HTF Mass flow rate"
Re_F= m_dot*D_1/(A_crosspipe*mu_f)
Pr_F= C_PF*mu_f/k_F
NU_F1=.0263*(Re_F^(3/4)) *(Pr_F^.4)
h_F=NU_F1*k_F/D_1
R_Ftotal=(ln(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradiant. That heat will calculated by following"
"m_dot=.05 [kg/s]" "HTF Mass flow rate"
Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
Q_F=Q_in
"BOILER: "
"Assume the flow in the tube is turbulant "
"Boiler has two componenets, Coil and boiler container. The HOT HTF flows through the coiles and loss
heat and Salt water
boil by nucleat boiling "
```

```
"Coil is made by 3/8 in copper pipe"
" We assume HTF leave the boiler at the 90C temprature"
"We are going to make three equations for heat and balance them for computing all variable "
"Firs heat we are going to calculate is the heat that the HTF loss by passing through the coil in the boiller
"
```



```
"Second we will caculating the heat flux that goes from the HTF by conduction to the salt water "
"Last one is the heat that which is caused increasing the inlet salt water temprature and boiling the salt
water, and it is
include the heat lost through the boiler body to the enviroment"
"FACTS "
"m_dot" "It is same
amount of HTF mass flow rate in solar collector "
"COIL Features "
"L_coil=25.92*convert(ft,m)" "Coil lenght "
D_1coil=.375*convert(in,m) "Coil ID"
r_1coil=D_1coil/2
D_2coil=.5*convert(in,m) "Coil OD"
r_2coil=D_2coil/2
K_coil=400 [W/m*K] "Thermal
conductivity factor "
A_coil1=pi*(D_1coil^2)/4 "Coil Inner
surface area "
A_coil2=pi*(D_2coil^2)/4 "Coil Outer
surface area"
A_crosscoil=(D_1coil^2)*pi/4
P_2coil=pi*D_2coil "Outter coil
Perimeter"
A_2coilsurface=P_2coil*L_coil
" We introduce T_avgFB. this is the average of the temprature of HTF inlet and oulet.
Temperature of the oule let is assumed, T_foutB=80 C"
"T_foutB=(90+273)" "HTF outlet
temperature "
T_finB=T_Fout
T_avgFB=(T_foutB+T_finB)/2 "HTF Average
temperature in the coil"
"T_avgFB=332"
"Use Look Up Table "
mu_fb=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgFB))-
5.02057*(exp((373/T_avgFB)^2))+2.31971*exp((373/T_avgFB)^3))
nu_fb=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgFB))-
0.000807195*(exp((373/T_avgFB)^2))+0.00104979*exp((
373/T_avgFB)^3))
k_fb=1.44720528E-01+8.23925584E-05*T_avgFB-3.99012752E-07*T_avgFB^2+3.42794460E-
10*T_avgFB^3
c_pfb=1.27992524E+03+2.45018746E+00*T_avgFB+1.37430217E-03*T_avgFB^2-1.06266283E-
06*T_avgFB^3
Pr_fb=C_pfb*mu_fb/k_fb "HTF Prandtle
at T_avgFB"
Re_fb=m_dot*d_1coil/(A_crosscoil*mu_fb) "HTF Renoulds
inside the coil tube "
Nu_Dfb=.0265*(Re_fb^(4/5))*(Pr_fb^.3)
" This Nuselt is calculated for turbolent flow while it gets cool"
h_fb=Nu_Dfb*k_fb/D_1coil
"HTF
```

Convection heat ttransfer coefficient inside the coil tube. "
Q_fb=m_dot*C_pfb*(T_finB-T_foutB) "Energy HTF
equation "

"Conduction Heat Transfer"
"The heat fulx from HTF to the outer surface of the coil tube"
"We introduce T_cbs, which is teperature on the outer surface of the coil tube"
"T_cbs=325"
R_totalFSB=((**ln**(r_2coil/r_1coil))/(2*pi*K_coil*L_coil))+(1/(2*pi*r_1coil*L_coil*h_fb)) "Total Thermal resistance for HTF and coil thickness"
Q_FSB=(T_avgFB-T_cbs)/R_totalFSB "Heat flux
through convection and conduction from HTF to surface of the coil tube"
Q_fb=Q_FSB
"Nucleate Boiling heat transfer "
"We assume the heat lost is negligible because of good insulation. this heat is consist the heat which is caused the boiling
and increasing the temprature of the inlet salt water to the saturation temperature."
"We assume the system is steady state and amount of the mass flow rate is equal to the amount of water which is vaporized.
"
"Water Properties"
C_SF=.0128
" P_water is pressure of the boiler"
P_water= .1 [atm]
T_sat=**t_sat**(***Water***,***P***=(P_water*__convert__(atm,Pa)))
DELTAh_vap=**enthalpy_vaporization**(***Water***,***T***=T_sat)
mu_fwater=**viscosity**(***Water***,***T***=T_sat,***x***=0)
v_fwater=**volume**(***Water***,***T***=T_sat,***x***=0)
cp_fwater=**specheat**(***Water***,***T***=T_sat,***x***=0)
Pr_fwater=**prandtl**(***Water***,***T***=T_sat,***x***=0)
rho_fwater=**density**(***Water***,***T***=T_sat,***x***=0)
rho_gwater=**density**(***Water***,***T***=T_sat,***x***=1)
sigma_fwater=**surfacetension**(***Water***,***T***=T_sat)
T_waterinlet=313
cp=**cp**(***Water***,***T***=T_waterinlet,***x***=0)
"Nucleate boiling heat per squar meter"
q_s=mu_fwater*DELTAh_vap*((g*(rho_fwater-rho_gwater)/sigma_fwater)^.5)*((cp_fwater*(T_cbs-T_sat)/(C_SF*
DELTAh_vap*Pr_fwater))^3)
q_sReal=q_s*A_2coilsurface "Real
nucleate boiling "
m_dot_v=q_sReal/DELTAh_vap
m_dot_v=.004336
"The total heat that transferredto the boiler is:"
Q_SB=q_sReal+m_dot_v*cp*(T_sat-T_waterinlet)
"All Heat are equal to each other "
Q_fb=Q_SB
Q_fb=Q_F
"**Efficiency**"
Q_sun=1000*rho_mirror*A_mirror ;
COP= m_dot_v*DELTAh_vap/Q_sun

Table 17 Turbulent flow in the solar collector, ṁ changes, (ṁ_V=0.004336 [kg/s], P_Boiler=0.1 [atm], Constant):

	m [kg/s]	P_{water} [atm]	L [m]	Q_{CF}	T_{avgF}	T_{avgFB}	T_{finB}	T_{cbs}	T_{osur}	T_{sat}	T_{foutB}	L_{coil} [m]	m_v	COP
Run 1	0.1766	0.1	11.81	10482	326.6	326.6	340.1	323.5	361.4	319.2	313	69.19	0.004336	0.8836
Run 2	0.1889	0.1	11.78	10482	325.7	325.7	338.4	323.2	359.2	319.2	313	82.85	0.004336	0.8862
Run 3	0.2013	0.1	11.75	10482	324.9	324.9	336.8	323	357.3	319.2	313	100.4	0.004336	0.8886
Run 4	0.2136	0.1	11.72	10482	324.2	324.2	335.5	322.7	355.5	319.2	313	123.6	0.004336	0.8907
Run 5	0.226	0.1	11.7	10482	323.6	323.6	334.3	322.5	353.9	319.2	313	154.7	0.004336	0.8926
Run 6	0.2383	0.1	11.67	10482	323.1	323.1	333.2	322.2	352.4	319.2	313	197.8	0.004336	0.8943
Run 7	0.2506	0.1	11.65	10482	322.6	322.6	332.2	321.9	351	319.2	313	259.2	0.004336	0.8959
Run 8	0.263	0.1	11.63	10482	322.2	322.2	331.3	321.7	349.8	319.2	313	350	0.004336	0.8973
Run 9	0.2753	0.1	11.62	10482	321.8	321.8	330.5	321.4	348.6	319.2	313	489.8	0.004336	0.8986
Run 10	0.2877	0.1	11.6	10482	321.4	321.4	329.8	321.2	347.5	319.2	313	718.8	0.004336	0.8999
Run 11	0.3	0.1	11.59	10482	321	321	329.1	320.9	346.5	319.2	313	1105	0.004336	0.901

Code for System when the flow is Turbulent in the solar collector, $\dot{m}$ changes, ($L = 16.2\ [m]$, $P_{Boiler} = 0.1\ [atm]$):

```
"Solar Collector"
rho_mirror=.99 "Mirror
reflectivity"
alpha_pipe=1 "Emessivity
which is equal absobility. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system. "
"At this stage we eleminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzman"
T_sun=1373 [K] "Temperature
on top of the atmosphier"
"** Physical Properties of solar collecttor**"
theta=70 "Angle of the
pipe to the vertical axis "
L=18.8 [m] "length of the
pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe
radias"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
epsilon_pipe=1
A_crosspipe=pi* r_1^2
"**Ambient and enviromental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperatrue "
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=P_amb ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
viscosity in assumed condition "
k_air=conductivity(Air,T=T_avg) "Thermal
```

Coductivity in assumed condition"
alpha_air=**thermaldiffusivity**(***Air***,***T***=T_avg,***P***=P_amb) "Thermal
Diffusivity at assumed condition"
Beta_air=1/T_avg "EXPANSION
COEFFICIENT FOR AIR"
g=9.81 [m/s^2]

"**Heat from the Sun**"
Ra_L=g*Beta_air*(**cos**(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overal convection heat transfer coefficient. (Based on only natural convection)"
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4))-(h_w*A_pipe*DELTAT) "The
heat that
will conduct to the HTF"
"Q_in=2900"
"For Heat that Transfer to the HTF by conduction and aonvection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system "
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(**exp**((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(**exp**(373/T_avgF))-
0.000807195*(**exp**((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
" m_dot=.1766 [kg/s]" "HTF Mass flow rate"
Re_F= m_dot*D_1/(A_crosspipe*mu_f)
Pr_F= C_PF*mu_f/k_F
NU_F1=.0263*(Re_F^(3/4)) *(Pr_F^.4)
h_F=NU_F1*k_F/D_1
R_Ftotal=(**ln**(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradiant. That heat will calculated by following"
Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
Q_F=Q_in
"BOILER: "
"Assume the flow in the tube is turbulant "
"Boiler has two componenets, Coil and boiler container. The HOT HTF flows through the coiles and loss
heat and Salt water
boil by nucleat boiling "
"Coil is made by 3/8 in copper pipe"
" We assume HTF leave the boiler at the 90C temprature"
"We are going to make three equations for heat and balance them for computing all variable "

"Firs heat we are going to calculate is the heat that the HTF loss by passing through the coil in the boiller "
"Second we will caculating the heat flux that goes from the HTF by conduction to the salt water "
"Last one is the heat that which is caused increasing the inlet salt water temprature and boiling the salt water, and it is

include the heat lost through the boiler body to the enviroment"
"FACTS "
"m_dot" "It is same
amount of HTF mass flow rate in solar collector "
"COIL Features "
"L_coil=25.92*convert(ft,m)" "Coil lenght "
D_1coil=.375***convert**(in,m) "Coil ID"
r_1coil=D_1coil/2
D_2coil=.5***convert**(in,m) "Coil OD"
r_2coil=D_2coil/2
K_coil=400 [W/m*K] "Thermal
conductivity factor "
A_coil1=pi*(D_1coil^2)/4 "Coil Inner
surface area "
A_coil2=pi*(D_2coil^2)/4 "Coil Outer
surface area"
A_crosscoil=(D_1coil^2)*pi/4
P_2coil=pi*D_2coil "Outter coil
Perimeter"
A_2coilsurface=P_2coil*L_coil
" We introduce T_avgFB. this is the average of the temprature of HTF inlet and oulet.
Temperature of the oule let is assumed, T_foutB=80 C"
"T_foutB=(90+273)" "HTF outlet
temperature "
T_finB=T_Fout
T_avgFB=(T_foutB+T_finB)/2 "HTF Average
temperature in the coil"
"T_avgFB=332"
"Use Look Up Table "
mu_fb=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgFB))-
5.02057*(**exp**((373/T_avgFB)^2))+2.31971*exp((373/T_avgFB)^3))
nu_fb=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgFB))-
0.000807195*(**exp**((373/T_avgFB)^2))+0.00104979*exp((
373/T_avgFB)^3))
k_fb=1.44720528E-01+8.23925584E-05*T_avgFB-3.99012752E-07*T_avgFB^2+3.42794460E-
10*T_avgFB^3
c_pfb=1.27992524E+03+2.45018746E+00*T_avgFB+1.37430217E-03*T_avgFB^2-1.06266283E-
06*T_avgFB^3
Pr_fb=C_pfb*mu_fb/k_fb "HTF Prandtle
at T_avgFB"
Re_fb=m_dot*d_1coil/(A_crosscoil*mu_fb) "HTF Renoulds
inside the coil tube "
Nu_Dfb=.0265*(Re_fb^(4/5))*(Pr_fb^.3)
" This Nuselt is calculated for turbolent flow while it gets cool"
h_fb=Nu_Dfb*k_fb/D_1coil
"HTF
Convection heat ttransfer coefficient inside the coil tube. "
Q_fb=m_dot*C_pfb*(T_finB-T_foutB) "Energy HTF
equation "

"Conduction Heat Transfer"
"The heat fulx from HTF to the outer surface of the coil tube"

"We introduce T_cbs, which is teperature on the outer surface of the coil tube"
"T_cbs=325"
R_totalFSB=((**ln**(r_2coil/r_1coil))/(2*pi*K_coil*L_coil))+(1/(2*pi*r_1coil*L_coil*h_fb)) "Total Thermal resistance for HTF and coil thickness"
Q_FSB=(T_avgFB-T_cbs)/R_totalFSB "Heat flux
through convection and conduction from HTF to surface of the coil tube"
Q_fb=Q_FSB
"Nucleate Boiling heat transfer "
"We assume the heat lost is negligible because of good insulation. this heat is consist the heat which is caused the boiling
and increasing the temprature of the inlet salt water to the saturation temperature."
"We assume the system is steady state and amount of the mass flow rate is equal to the amount of water which is vaporized.
"
"Water Properties"
C_SF=.0128
" P_water is pressure of the boiler"
P_water= .1 [atm]
T_sat=**t_sat**(***Water***,***P***=(P_water***convert**(atm,Pa)))
DELTAh_vap=**enthalpy_vaporization**(***Water***,***T***=T_sat)
mu_fwater=**viscosity**(***Water***,***T***=T_sat,***x***=0)
v_fwater=**volume**(***Water***,***T***=T_sat,***x***=0)
cp_fwater=**specheat**(***Water***,***T***=T_sat,***x***=0)
Pr_fwater=**prandtl**(***Water***,***T***=T_sat,***x***=0)
rho_fwater=**density**(***Water***,***T***=T_sat,***x***=0)
rho_gwater=**density**(***Water***,***T***=T_sat,***x***=1)
sigma_fwater=**surfacetension**(***Water***,***T***=T_sat)
T_waterinlet=313
cp=**cp**(***Water***,***T***=T_waterinlet,***x***=0)
"Nucleate boiling heat per squar meter"
q_s=mu_fwater*DELTAh_vap*((g*(rho_fwater-rho_gwater)/sigma_fwater)^.5)*((cp_fwater*(T_cbs-T_sat)/(C_SF*
DELTAh_vap*Pr_fwater))^3)
q_sReal=q_s*A_2coilsurface "Real
nucleate boiling "
m_dot_v=q_sReal/DELTAh_vap
"m_dot_v=.004336"
"The total heat that transferredto the boiler is:"
Q_SB=q_sReal+m_dot_v*cp*(T_sat-T_waterinlet)
"All Heat are equal to each other "
Q_fb=Q_SB
Q_fb=Q_F
"**Efficiency**"
Q_sun=1000*rho_mirror*A_mirror ;
COP= m_dot_v*DELTAh_vap/Q_sun

Table 18: Turbulent flow in the solar collector, m˙ changes, (L=18.8 [m], P_Boiler=0.1 [atm], Constant):

	m	P_{water}	L	Q_{CF}	T_{avgF}	T_{avgFB}	T_{finB}	T_{cbs}	T_{osur}	T_{sat}	T_{foutB}	L_{coil}	m_v	COP
	[kg/s]	[atm]	[m]									[m]		
Run 3	0.2014	*0.1*	*18.8*	*14561*	*329.4*	*329.4*	*345.9*	*324.4*	*352.3*	*319.2*	*313*	*51.8*	*0.006023*	*0.8952*
Run 4	0.2137	*0.1*	*18.8*	*14592*	*328.6*	*328.6*	*344.1*	*324.2*	*350.6*	*319.2*	*313*	*58.13*	*0.006036*	*0.8971*
Run 5	0.226	*0.1*	*18.8*	*14620*	*327.7*	*327.7*	*342.5*	*324*	*349*	*319.2*	*313*	*65.45*	*0.006048*	*0.8988*
Run 6	0.2384	*0.1*	*16.2*	*14645*	*327*	*327*	*341*	*323.8*	*347.6*	*319.2*	*313*	*74*	*0.006059*	*0.9004*
Run 7	0.2507	*0.1*	*16.2*	*14668*	*326.4*	*326.4*	*339.7*	*323.7*	*346.3*	*319.2*	*313*	*84.07*	*0.006068*	*0.9018*
Run 8	0.263	*0.1*	*16.2*	*14689*	*325.8*	*325.8*	*338.5*	*323.5*	*345.1*	*319.2*	*313*	*96.02*	*0.006077*	*0.9031*
Run 9	0.2753	*0.1*	*16.2*	*14708*	*325.2*	*325.2*	*337.4*	*323.3*	*344.1*	*319.2*	*313*	*110.3*	*0.006085*	*0.9042*
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Run 11	0.3	*0.1*	*18.8*	*14742*	*324.3*	*324.3*	*335.5*	*322.9*	*342.1*	*319.2*	*313*	*148.9*	*0.006099*	*0.9063*

Code for System when the flow is Turbulent in the solar collector, $\dot{m}_V$ changes, ($\dot{m} = 0.1708 \left[\frac{kg}{s}\right], P_{Boiler} = 0.1\ [atm]$):

```
"Solar Collector"
rho_mirror=.99 "Mirror
reflectivity"
alpha_pipe=1 "Emissivity
which is equal absobility. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system. "
"At this stage we eleminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzman"
T_sun=1373 [K] "Temperature
on top of the atmosphier"
"** Physical Properties of solar collecttor**"
theta=70 "Angle of the
pipe to the vertical axis "
"L=30*convert(ft,m) " "length of the
pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe
radias"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
epsilon_pipe=1
A_crosspipe=pi*r_1^2
"**Ambient and enviromental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperatrue "
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=P_amb ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
viscosity in assumed condition "
k_air=conductivity(Air,T=T_avg) "Thermal
```

Coductivity in assumed condition"
alpha_air=**thermaldiffusivity**(***Air***,***T***=T_avg,***P***=P_amb) "Thermal
Diffusivity at assumed condition"
Beta_air=1/T_avg "EXPANSION
COEFFICIENT FOR AIR"

g=9.81 [m/s^2]
"**Heat from the Sun**"
Ra_L=g*Beta_air*(**cos**(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overal convection heat transfer coefficient. (Based on only natural convection)"
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4))-(h_w*A_pipe*DELTAT) "The
heat that
will conduct to the HTF"
"Q_in=2900"
"For Heat that Transfer to the HTF by conduction and aonvection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system "
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(**exp**((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(**exp**(373/T_avgF))-
0.000807195*(**exp**((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
m_dot=.1766 [kg/s] "HTF Mass flow rate"
Re_F= m_dot*D_1/(A_crosspipe*mu_f)
Pr_F= C_PF*mu_f/k_F
NU_F1=.0263*(Re_F^(3/4)) *(Pr_F^.4)
h_F=NU_F1*k_F/D_1 "Assumed that
there is a laminar flow in the tubes"
R_Ftotal=(**ln**(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradiant. That heat will calculated by following"
Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
Q_F=Q_in
"BOILER: "
"Assume the flow in the tube is turbulant "
"Boiler has two componenets, Coil and boiler container. The HOT HTF flows through the coiles and loss
heat and Salt water
boil by nucleat boiling "
"Coil is made by 3/8 in copper pipe"
" We assume HTF leave the boiler at the 90C temprature"

"We are going to make three equations for heat and balance them for computing all variable "
"Firs heat we are going to calculate is the heat that the HTF loss by passing through the coil in the boiller "
"Second we will caculating the heat flux that goes from the HTF by conduction to the salt water"
"Last one is the heat that which is caused increasing the inlet salt water temprature and boiling the salt water, and it is

include the heat lost through the boiler body to the enviroment"
"FACTS "
"m_dot" "It is same amount of HTF mass flow rate in solar collector "
"COIL Features "
"L_coil=25.92*convert(ft,m)" "Coil lenght "
D_1coil=.375***convert**(in,m) "Coil ID"
r_1coil=D_1coil/2
D_2coil=.5***convert**(in,m) "Coil OD"
r_2coil=D_2coil/2
K_coil=400 [W/m*K] "Thermal conductivity factor "
A_coil1=pi*(D_1coil^2)/4 "Coil Inner surface area "
A_coil2=pi*(D_2coil^2)/4 "Coil Outer surface area"
A_crosscoil=(D_1coil^2)*pi/4
P_2coil=pi*D_2coil "Outter coil Perimeter"
A_2coilsurface=P_2coil*L_coil
" We introduce T_avgFB. this is the average of the temprature of HTF inlet and oulet. Temperature of the oule let is assumed, T_foutB=80 C"
"T_foutB=(90+273)" "HTF outlet temperature "
T_finB=T_Fout
T_avgFB=(T_foutB+T_finB)/2 "HTF Average temperature in the coil"
"T_avgFB=332"
"Use Look Up Table "
mu_fb=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgFB))-5.02057*(**exp**((373/T_avgFB)^2))+2.31971*exp((373/T_avgFB)^3))
nu_fb=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgFB))-0.000807195*(**exp**((373/T_avgFB)^2))+0.00104979*exp((373/T_avgFB)^3))
k_fb=1.44720528E-01+8.23925584E-05*T_avgFB-3.99012752E-07*T_avgFB^2+3.42794460E-10*T_avgFB^3
c_pfb=1.27992524E+03+2.45018746E+00*T_avgFB+1.37430217E-03*T_avgFB^2-1.06266283E-06*T_avgFB^3
Pr_fb=C_pfb*mu_fb/k_fb "HTF Prandtle at T_avgFB"
Re_fb=m_dot*d_1coil/(A_crosscoil*mu_fb) "HTF Renoulds inside the coil tube "
Nu_Dfb=.0265*(Re_fb^(4/5))*(Pr_fb^.3)
" This Nuselt is calculated for turbolent flow while it gets cool"
h_fb=Nu_Dfb*k_fb/D_1coil
"HTF Convection heat ttransfer coefficient inside the coil tube. "
Q_fb=m_dot*C_pfb*(T_finB-T_foutB) "Energy HTF

```
equation "
"Conduction Heat Transfer"
"The heat fulx from HTF to the outer surface of the coil tube"
```

```
"We introduce T_cbs, which is teperature on the outer surface of the coil tube"
"T_cbs=325"
R_totalFSB=((ln(r_2coil/r_1coil))/(2*pi*K_coil*L_coil))+(1/(2*pi*r_1coil*L_coil*h_fb)) "Total Thermal
resistance for HTF and coil thickness"
Q_FSB=(T_avgFB-T_cbs)/R_totalFSB "Heat flux
through convection and conduction from HTF to surface of the coil tube"
Q_fb=Q_FSB
"Nucleate Boiling heat transfer "
"We assume the heat lost is negligible because of good insulation. this heat is consist the heat which is
caused the boiling
and increasing the temprature of the inlet salt water to the saturation temperature."
"We assume the system is steady state and amount of the mass flow rate is equal to the amount of water
which is vaporized.
"
"Water Properties"
C_SF=.0128
" P_water is pressure of the boiler"
P_water= .1 [atm]
T_sat=t_sat(Water,P=(P_water*convert(atm,Pa)) )
DELTAh_vap=enthalpy_vaporization(Water,T=T_sat)
mu_fwater=viscosity(Water,T=T_sat,x=0)
v_fwater=volume(Water,T=T_sat,x=0)
cp_fwater=specheat(Water,T=T_sat,x=0)
Pr_fwater=prandtl(Water,T=T_sat,x=0)
rho_fwater=density(Water,T=T_sat,x=0)
rho_gwater=density(Water,T=T_sat,x=1)
sigma_fwater=surfacetension(Water,T=T_sat)
T_waterinlet=313
cp=cp(Water,T=T_waterinlet,x=0)
"Nucleate boiling heat per squar meter"
q_s=mu_fwater*DELTAh_vap*((g*(rho_fwater-rho_gwater)/sigma_fwater)^.5)*((cp_fwater*(T_cbs-
T_sat)/(C_SF*
DELTAh_vap*Pr_fwater))^3)
q_sReal=q_s*A_2coilsurface "Real
nucleate boiling "
m_dot_v=q_sReal/DELTAh_vap
"m_dot_v=.004336"
"The total heat that transferredto the boiler is:"
Q_SB=q_sReal+m_dot_v*cp*(T_sat-T_waterinlet)
"All Heat are equal to each other "
Q_fb=Q_SB
Q_fb=Q_F
"**Efficiency**"
Q_sun=1000*A_mirror
COP= m_dot_v*DELTAh_vap/Q_sun
```

Table 19 Turbulent flow in the solar collector, ṁ _Vchanges, (ṁ =0.1766 [kg/s], P_Boiler=0.1 [atm], Constant):

	m_v	m [kg/s]	P_{water} [atm]	L [m]	Q_{CF}	T_{avgF}	T_{avgFB}	T_{finB}	T_{cbs}	T_{osur}	T_{sat}	T_{foutB}	L_{coil} [m]	COP
Run 1	0.003	0.1767	0.1	8.321	7252	322.4	322.4	331.9	321.7	372.6	319.2	313	227	0.8593
Run 2	0.0034	0.1767	0.1	9.362	8219	323.7	323.7	334.3	322.4	368.1	319.2	313	133.1	0.8656
Run 3	0.0038	0.1767	0.1	10.41	9186	324.9	324.9	336.8	322.9	364.7	319.2	313	94.44	0.8702
Run 4	0.0042	0.1767	0.1	11.46	10153	326.1	326.1	339.3	323.3	362.1	319.2	313	74.12	0.8738
Run 5	0.0046	0.1767	0.1	12.51	11120	327.4	327.4	341.7	323.7	360.1	319.2	313	61.77	0.8765
Run 6	0.005	0.1767	0.1	13.57	12087	328.6	328.6	344.2	324.1	358.5	319.2	313	53.52	0.8785
Run 7	0.0054	0.1767	0.1	14.62	13054	329.8	329.8	346.6	324.4	357.4	319.2	313	47.64	0.8801
Run 8	0.0058	0.1767	0.1	15.69	14021	331	331	349	324.7	356.5	319.2	313	43.23	0.8812
Run 9	0.0062	0.1767	0.1	16.75	14988	332.2	332.2	351.4	325	355.9	319.2	313	39.8	0.8821
Run 10	0.0066	0.1767	0.1	17.82	15954	333.4	333.4	353.9	325.2	355.5	319.2	313	37.05	0.8826
Run 11	0.007	0.1767	0.1	18.89	16921	334.6	334.6	356.3	325.5	355.3	319.2	313	34.8	0.883

Code for System when the flow is Turbulent in the solar collector, and *L* is variable:

```
"Solar Collector"
rho_mirror=.99 "Mirror
reflectivity"
alpha_pipe=1 "Emessivity
which is equal absobility. Because we assume the pipe as a black body"
"We assume system is a quassi- steady state system. "
"At this stage we eleminate the force convection term and do our calculation based on only natural
convection. "
Sigma= 5.67*(10^(-8)) [W/(m^2*K^4)] "Stefan
Boltzman"
T_sun=1373 [K] "Temperature
on top of the atmosphier"
"** Physical Properties of solar collecttor**"
theta=70 "Angle of the
pipe to the vertical axis "
"L=90 [m]" "length of the
pipe"
D_2=1.24*convert(inch,m) "Outer pipe
diameter"
D_1=1*convert(inch,m) "Inner pipe
diameter "
r_2=D_2/2 "Outer pipe
radias"
r_1=D_1/2 "Inner pipe
radias"
k_cop=400[W/(m*K)] "Copper
Thermal Conductivity coefficient"
A_pipe=pi*D_2*L "Pipe Surface
area"
A_mirror=(39.5*convert(inch,m)) *L "Mirror
Projected area on the plane that contain two edges of the aperture"
epsilon_pipe=1
A_crosspipe=pi*r_1^2
"**Ambient and enviromental Properties**"
"T_osur=600" " Temperature
of the pipe outer wall surface "
T_amb=293[K]
T_avg=(T_amb+T_osur)/2 "Average
Temperature B/W ambient temperature and outer pipe wall temperatrue "
DELTAT=T_osur-T_amb "Temperature
difference B/W Outer pipe wall temperature and ambient temperature "
"** Air Properties **"
P_amb=1*convert(atm,Pa)
mu_air=viscosity(Air,T=T_avg) "Viscosity of air
at T_avg"
rho_air=density(Air,T=T_avg,P=P_amb ) "Density of the
air at T_avg and, pressure at1 atm "
nu_air=kinematicviscosity(Air,T=T_avg,P=P_amb) "Kinematic
viscosity in assumed condition "
```

```
k_air=conductivity(Air,T=T_avg) "Thermal
Coductivity in assumed condition"
alpha_air=thermaldiffusivity(Air,T=T_avg,P=P_amb) "Thermal
Diffusivity at assumed condition"
Beta_air=1/T_avg "EXPANSION
```



```
COEFFICIENT FOR AIR"
g=9.81 [m/s^2]
"**Heat from the Sun**"
Ra_L=g*Beta_air*(cos(theta))*DELTAT*(L^3)/(nu_air*alpha_air) "Rayleigh
number for length the tube "
h_w=.524*k_air*(Ra_L^.25)/L "Average
overal convection heat transfer coefficient. ( Based on only natural convection)"
Q_in=(A_mirror*rho_mirror*1000)-(A_pipe*epsilon_pipe*Sigma*(T_osur^4))-(h_w*A_pipe*DELTAT) "The
heat that
will conduct to the HTF"
"Q_in=2900"
"For Heat that Transfer to the HTF by conduction and aonvection"
"**HTF Properties**"
T_Fin=313[K] "Inlet HTF
Temperature to the solar collector system "
"T_Fout=413 " "Outlet HTF
Temperature from the solar collector system"
T_avgF=(T_Fin+T_Fout)/2 "Average
Temperature HTF B/W inlet and outlet"
k_F= 1.44720528E-01+8.23925584E-05*T_avgF-3.99012752E-07*T_avgF^2+3.42794460E-
10*T_avgF^3
mu_f=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgF))-
5.02057*(exp((373/T_avgF)^2))+2.31971*exp((373/T_avgF)^3))
nu_f=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgF))-
0.000807195*(exp((373/T_avgF)^2))+0.00104979*exp((373/
T_avgF)^3))
C_PF=1.27992524E+03+2.45018746E+00*T_avgF+1.37430217E-03*T_avgF^2-1.06266283E-
06*T_avgF^3
m_dot=.3 [kg/s] "HTF Mass flow rate"
Re_F= m_dot*D_1/(A_crosspipe*mu_f)
Pr_F= C_PF*mu_f/k_F
NU_F1=.0263*(Re_F^(3/4)) *(Pr_F^.4)
h_F=NU_F1*k_F/D_1
R_Ftotal=(ln(r_2/r_1)/(2*pi*L*k_cop))+(1/(2*pi*r_1*L*h_F)) "Total heat
transfer resistance for Q_CF"
DELTAT_F=T_osur-T_avgF
Q_CF=(A_pipe/R_Ftotal)*DELTAT_F "Heat that
transferredto HTF by Convection"
Q_CF=Q_in
"Heat which is computed based on temperature gradiant. That heat will calculated by following"
"m_dot=.05 [kg/s]" "HTF Mass flow rate"
Q_F=m_dot*C_PF*(T_Fout-T_Fin) "Amount of heat that is involved increasing HTF temperature"
Q_F=Q_in
"BOILER: "
"Assume the flow in the tube is turbulant "
"Boiler has two componenets, Coil and boiler container. The HOT HTF flows through the coiles and loss
heat and Salt water
boil by nucleat boiling "
"Coil is made by 3/8 in copper pipe"
```

```
" We assume HTF leave the boiler at the 90C temprature"
"We are going to make three equations for heat and balance them for computing all variable "
"Firs heat we are going to calculate is the heat that the HTF loss by passing through the coil in the boiller
"
```


```
"Second we will caculating the heat flux that goes from the HTF by conduction to the salt water "
"Last one is the heat that which is caused increasing the inlet salt water temprature and boiling the salt
water, and it is
include the heat lost through the boiler body to the enviroment"
"FACTS "
"m_dot" "It is same
amount of HTF mass flow rate in solar collector "
"COIL Features "
"L_coil=25.92*convert(ft,m)" "Coil lenght "
D_1coil=.375*convert(in,m) "Coil ID"
r_1coil=D_1coil/2
D_2coil=.5*convert(in,m) "Coil OD"
r_2coil=D_2coil/2
K_coil=400 [W/m*K] "Thermal
conductivity factor "
A_coil1=pi*(D_1coil^2)/4 "Coil Inner
surface area "
A_coil2=pi*(D_2coil^2)/4 "Coil Outer
surface area"
A_crosscoil=(D_1coil^2)*pi/4
P_2coil=pi*D_2coil "Outter coil
Perimeter"
A_2coilsurface=P_2coil*L_coil
" We introduce T_avgFB. this is the average of the temprature of HTF inlet and oulet.
Temperature of the oule let is assumed, T_foutB=80 C"
"T_foutB=(90+273)"
T_Fin=T_foutB "HTF outlet
temperature "
"T_finB=T_Fout"
T_avgFB=(T_foutB+T_finB)/2 "HTF Average
temperature in the coil"
"T_avgFB=332"
"Use Look Up Table "
mu_fb=1.44E-3*(-4.27913+4.6376*(exp(373/T_avgFB))-
5.02057*(exp((373/T_avgFB)^2))+2.31971*exp((373/T_avgFB)^3))
nu_fb=1.44E-3*(-0.000669797+0.000457831*(exp(373/T_avgFB))-
0.000807195*(exp((373/T_avgFB)^2))+0.00104979*exp((
373/T_avgFB)^3))
k_fb=1.44720528E-01+8.23925584E-05*T_avgFB-3.99012752E-07*T_avgFB^2+3.42794460E-
10*T_avgFB^3
c_pfb=1.27992524E+03+2.45018746E+00*T_avgFB+1.37430217E-03*T_avgFB^2-1.06266283E-
06*T_avgFB^3
Pr_fb=C_pfb*mu_fb/k_fb "HTF Prandtle
at T_avgFB"
Re_fb=m_dot*d_1coil/(A_crosscoil*mu_fb) "HTF Renoulds
inside the coil tube "
Nu_Dfb=.0265*(Re_fb^(4/5))*(Pr_fb^.3)
" This Nuselt is calculated for turbolent flow while it gets cool"
h_fb=Nu_Dfb*k_fb/D_1coil
"HTF
```

```
Convection heat ttransfer coefficient inside the coil tube. "
Q_fb=m_dot*C_pfb*(T_finB-T_foutB) "Energy HTF
equation "
```

```
"Conduction Heat Transfer"
"The heat fulx from HTF to the outer surface of the coil tube"
"We introduce T_cbs, which is teperature on the outer surface of the coil tube"
"T_cbs=325"
R_totalFSB=((ln(r_2coil/r_1coil))/(2*pi*K_coil*L_coil))+(1/(2*pi*r_1coil*L_coil*h_fb)) "Total Thermal
resistance for HTF and coil thickness"
Q_FSB=(T_avgFB-T_cbs)/R_totalFSB "Heat flux
through convection and conduction from HTF to surface of the coil tube"
Q_fb=Q_FSB
"Nucleate Boiling heat transfer "
"We assume the heat lost is negligible because of good insulation. this heat is consist the heat which is
caused the boiling
and increasing the temprature of the inlet salt water to the saturation temperature."
"We assume the system is steady state and amount of the mass flow rate is equal to the amount of water
which is vaporized.
"
"Water Properties"
C_SF=.0128
" P_water is pressure of the boiler"
P_water= .1 [atm]
T_sat=t_sat(Water,P=(P_water*convert(atm,Pa)) )
DELTAh_vap=enthalpy_vaporization(Water,T=T_sat)
mu_fwater=viscosity(Water,T=T_sat,x=0)
v_fwater=volume(Water,T=T_sat,x=0)
cp_fwater=specheat(Water,T=T_sat,x=0)
Pr_fwater=prandtl(Water,T=T_sat,x=0)
rho_fwater=density(Water,T=T_sat,x=0)
rho_gwater=density(Water,T=T_sat,x=1)
sigma_fwater=surfacetension(Water,T=T_sat)
T_waterinlet=313
cp=cp(Water,T=T_waterinlet,x=0)
"Nucleate boiling heat per squar meter"
q_s=mu_fwater*DELTAh_vap*((g*(rho_fwater-rho_gwater)/sigma_fwater)^.5)*((cp_fwater*(T_cbs-
T_sat)/(C_SF*
DELTAh_vap*Pr_fwater))^3)
q_sReal=q_s*A_2coilsurface "Real
nucleate boiling "
m_dot_v=q_sReal/DELTAh_vap
"m_dot_v=.004336"
"The total heat that transferredto the boiler is:"
Q_SB=q_sReal+m_dot_v*cp*(T_sat-T_waterinlet)
"All Heat are equal to each other "
Q_fb=Q_SB
Q_fb=Q_F
"**Efficiency**"
Q_sun=1000*rho_mirror*A_mirror ;
COP= m_dot_v*DELTAh_vap/Q_sun
```

Table 20 Turbulent flow in the solar collector, and L is variable:

	L	COP	m	m_v
	[m]		[kg/s]	
Run 1	21	*0.9218*	*0.3*	*0.01098*
Run 2	22.82	*0.9219*	*0.3*	*0.01193*
Run 3	24.63	*0.9217*	*0.3*	*0.01288*
Run 4	26.45	*0.9214*	*0.3*	*0.01383*
Run 5	28.27	*0.921*	*0.3*	*0.01477*
Run 6	30.08	*0.9205*	*0.3*	*0.01571*
Run 7	31.9	*0.9199*	*0.3*	*0.01665*
Run 8	33.71	*0.9192*	*0.3*	*0.01758*
Run 9	35.53	*0.9184*	*0.3*	*0.01852*
Run 10	37.35	*0.9176*	*0.3*	*0.01944*
Run 11	39.16	*0.9168*	*0.3*	*0.02037*
Run 12	40.98	*0.9159*	*0.3*	*0.0213*
Run 13	42.8	*0.915*	*0.3*	*0.02222*
Run 14	44.61	*0.914*	*0.3*	*0.02314*
Run 15	46.43	*0.9131*	*0.3*	*0.02405*
Run 16	48.24	*0.912*	*0.3*	*0.02497*
Run 17	50.06	*0.911*	*0.3*	*0.02588*
Run 18	51.88	*0.91*	*0.3*	*0.02678*
Run 19	53.69	*0.9089*	*0.3*	*0.02769*
Run 20	55.51	*0.9078*	*0.3*	*0.02859*
Run 21	57.33	*0.9067*	*0.3*	*0.02949*
Run 22	59.14	*0.9056*	*0.3*	*0.03039*
Run 23	60.96	*0.9045*	*0.3*	*0.03128*
Run 24	62.78	*0.9033*	*0.3*	*0.03217*
Run 25	64.59	*0.9021*	*0.3*	*0.03306*
Run 26	66.41	*0.901*	*0.3*	*0.03395*
Run 27	68.22	*0.8998*	*0.3*	*0.03483*
Run 28	70.04	*0.8986*	*0.3*	*0.03571*
Run 29	71.86	*0.8974*	*0.3*	*0.03659*
Run 30	73.67	*0.8962*	*0.3*	*0.03746*
Run 31	75.49	*0.895*	*0.3*	*0.03833*
Run 32	77.31	*0.8937*	*0.3*	*0.0392*

Table 21: Parametric table for calculating unsteady condition when the HTF mass flow rate is 0.2 [kg/s], and water vapor mass flow rate is 0.0004336 [kg/s]

	P_{water}	h_{fb}	Q_{in}	T_{avgF}	T_{avgFB}	T_{cbs}	T_{osur}	T_{sat}	L [m]	L_{coil} [m]	C_{PF}	ρ_{fwater}	ρ_{fb}
Run 1	0.05	1781	10381	324.9	324.9	312.7	357.7	306.3	11.64	16.1	2185	994.6	838
Run 2	0.05667	1781	10398	324.9	324.9	314.7	357.6	308.5	11.66	19.18	2185	993.9	838
Run 3	0.06333	1781	10414	324.9	324.9	316.4	357.6	310.5	11.68	23.06	2185	993.1	837.9
Run 4	0.07	1782	10429	324.9	324.9	317.9	357.6	312.4	11.69	28.1	2185	992.5	837.9
Run 5	0.07667	1782	10442	324.9	324.9	319.3	357.5	314.1	11.71	34.87	2185	991.8	837.9
Run 6	0.08333	1782	10454	325	325	320.5	357.5	315.7	11.72	44.38	2185	991.2	837.8
Run 7	0.09	1783	10466	325	325	321.6	357.5	317.2	11.73	58.53	2185	990.6	837.8
Run 8	0.09667	1783	10476	325	325	322.6	357.5	318.6	11.75	81.28	2185	990	837.7
Run 9	0.1033	1783	10487	325	325	323.4	357.4	319.9	11.76	122	2185	989.4	837.7
Run 10	0.11	1783	10496	325	325	324.1	357.4	321.1	11.77	208.2	2185	988.9	837.7

Table 22: Constant of Equation 13 (Zukauskas relation) for cylinder in cross flow

Re_D	C	m
1-40	0.75	0.4
40-1000	0.51	0.5
10^3 -$2x10^5$	0.26	0.6
$2x10^5$ -10^6	0.076	0.7