MEGN-571 Final Report: Heat Transfer within a Concentrated Solar Thermal Facility

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Abstract:

A Concentrated Solar Thermal (CST) facility has been modeled with the intent of analyzing the heat transfer between the solar tower exterior face to the molten salt tubes for the purpose of electricity generation through exposing the molten salt to a second tank cycle, generating steam. The analysis has been completed as required by constructing a model in MATLAB, which consists of solar radiation with non-uniform heating to a tube within a bank, which is further developed with a two dimensional flow model of the fluid within the tube. The presented application of heat transfer is supported by research and similar applications demonstrated within facility efficiency studies, as well as coursework, and the energy industry.

Introduction with Literature Review:

Concentrated Solar Thermal (CST) plants have become a prominent and extensively utilized source of renewable energy in modern power generation. Although variable in power output, akin to photovoltaics and wind energy, research into solar energy collection and storage have made CSTs a viable alternative to LNG and other non-renewable energy sources. These facilities function by focusing solar irradiation to heat a thermal medium. This thermal medium can transfer heat to a working fluid, which then drives a generator to produce electricity. This component of the facility drives the amount of heat required for functionality, as it is dependent on the power cycle efficiency [1]. The required heat and specific heat capacity of the thermal medium can then be utilized to derive the inlet and outlet temperatures and mass flow rate required at the receiver, as they are dependent on one another [1]. Four primary CST methodologies exist: parabolic troughs, central receiver towers, parabolic dish-Stirling engine systems, and linear Fresnel reflectors, all of which heat a fluid medium in a different manner [1]. However, given the intermittent availability of sunlight essential for plant operation, thermal energy storage systems are necessary to adapt electrical power production to transient and overnight demand. Conventional energy storage systems, such as lead-acid batteries, are constrained by limited energy capacities and are prone to rapid degradation due to frequent ‘deep’ discharges. Consequently, they have proven to be largely unsuitable for large scale commercial solar operations [2]. Rather, CST facilities use specialized materials designed to function as both a heat transfer and energy storage medium. Many operations utilize high temperature eutectic synthetic oil mixtures or popular “solar salts” such as HitecXL (48% $Ca(NO_3)_2$, 7% $NaNO_3$, 45% KNO_3) or binary salt mixtures (60% $NaNO_3$, 40% KNO_3) [3]. However, the efficacy of molten salts is under question given their high freezing points (ranging from 120°C - 220°C) and high parasitic consumptions during discharge phases. To strengthen a model of a real world CST application beyond the configuration of the facility itself, the NREL National Solar Radiation Database can be used as well to acquire Direct Normal Irradiation values for a given time period in hourly intervals [6]. These values will be injected into the constructed models to provide a high quality representation of not only the steady state model, but a transitive application that varies radiative heat flux with time.

For the purpose of the project, a central receiver tower concept, specifically the Crescent Dunes Solar Energy Plant, was utilized with heliostat reflectors directing sunlight towards the tower receiver with a 360 degree application [5]. The CST receiver consists of a number of tube banks surrounding the tower, which for the purpose of the model will be simplified into one shell around what would be the adiabatic backing of the tube banks, which is shown in Figure 1.

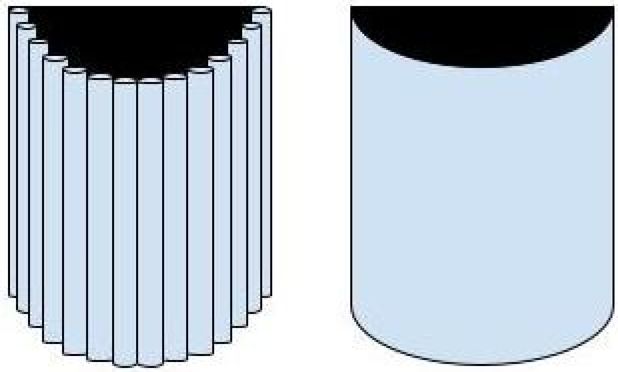


Figure 1: Example of tube receiver versus simplified shell.

Based on these factors, the heat transfer after the concentrated solar energy (solar flux) hits the tower receiver panel, specifically from the outer tube (shell) face to the solar salt was modeled in a one dimensional configuration, with the radiative heat flux being uniform along the length of the tube, but variable with time. Radiative and convective losses to the environment are also accounted for in this model. Considering the two dimensional model, the one dimensional model is used as the framework for the heat transfer to the fluid as well as losses, and the flow of the solar salt within the tube is considered with the pipe wall included. The two dimensional model also simplifies the tube banks surrounding the tower into a shell, where molten solar salt flows between the outer wall and inner adiabatic surface. The purpose of the constructed two dimensional model is to demonstrate conduction to the fluid from the tube wall, as well as to validate the results generated from the one dimensional MATLAB model, analyzing the heat transfer across the flow. Both models are discussed in greater detail in future sections, with emphasis on the modeling approach, scope, and validation plan.

Expected Objectives:

- Construct a model within MATLAB of the radiative heat transfer between radiative solar thermal energy directed at a central receiver and the molten salt flow within a Concentrated Solar Thermal (CST) plant architecture.
- Apply an Energy Balance within the model with regards to the radiative heat flux into the tubes and therefore to the salt through conduction, radiative losses to the environment, and convective losses to the environment.
- Determine the solar salt flow rate through the tubes, considering the heat transfer from the radiative source that varies with time based on collected NREL NSRDB weather data, to achieve a certain mean outlet temperature.
- Investigate the impacts of altering parameters such as receiver height, tube wall thickness, and wind speed on the outlet mean fluid temperature with averaged heat flux values based on NREL NSRDB weather data.

- Construct a 2-D flow simulation utilizing SolidWorks Flow Simulation to validate the MATLAB model, as well as applying other applicable validation methods holistically.

Expected Outcomes:

- Learning Outcome One will be accounted for by demonstrating a deeper knowledge and understanding of the application of energy balances to control volumes and surfaces, which the modeling of will be required for various components within the project, along with the presence of solutions for steady and transient temperatures and fluxes throughout the overarching system.
- Learning Outcome Two will be demonstrated through the modeling of heat transfers throughout different components and systems within a CST facility, and the required usage of differential and nonlinear systems of equations within the solutions.
- Learning Outcome Six will be present throughout the duration of the project at hand, as all components of the CST scenario and its corresponding model will require in-depth support and analysis which will be presented through clear documentation demonstrating required aspects of findings.

Modeling Approach and Scope:

In order to model the Concentrated Solar Thermal (CST) plants, heat generation will be neglected, but this doesn't hinder the salt to store the heat energy from the reflected sunlight. The receiver itself will be modeled after the Crescent Dunes Solar Energy Plant in Tonopah Nevada. At this plant, the receiver has a diameter of 15.8 m and a height of 30.5 m and is made up of 14 panels each consisting of 66 identical salt tubes [5]. Each tube is approximately 5 cm in diameter, with a 1.65 mm tube wall, as well as an absorptivity of 0.95, an emissivity of 0.89, and a heat transfer coefficient of 400 W/m*K [5]. As stated earlier, the tube banks will be simplified into a shell, which will carry an outer and inner diameter of 15.8 m and 15.7 m respectively, demonstrating the 5 cm diameter of the tubes and accounting for the wall thickness. Considering the inlet and outlet temperatures of the CST facility fluid flow, 290 C and 565 C will be utilized as the temperatures for the cold and hot sides, respectively. Considering the molten salt, the properties for a binary salt mixture, consisting of 60% $NaNO_3$, 40% KNO_3 were used in the construction of the model. The mixture has a thermal conductivity of 0.4407 W/m*K, a specific heat capacity of 1442.3 J/kg*K, a density of 2085.5 kg/m^3, a dynamic viscosity of approximately 1.529E-3 mPa*s, and a thermal diffusivity of approximately 1.904E-7 m^2/s [5]. All values are representative of the molten salt utilized by the Crested Dunes Solar Energy Plant. These factors are incorporated into the one dimensional and two dimensional models in an effort to provide the most accurate depiction possible of the CST facility.

The model will be implemented in the daytime, where nighttime is disregarded as there will not be any solar irradiation during this time. The radiative heat flux into the model will be drawn from the Direct Normal Irradiation values provided by the NREL NSRB, which provides hourly DNI data at the coordinates (38.25, -117.38) of the Crescent Dunes Solar Energy Plant for a given time interval [6]. Models will be constructed for variation throughout daylight hours for a seven day period, with DNI data for the 14 daylight hours from 6/1/2023 - 6/7/2023, which can be seen in Table 1, and variation throughout the month of June 2023, utilizing a daily average value for flux. The value of radiative heat flux to the receiver (annulus) is derived by multiplying the DNI values against a ratio of the surface area of the heliostat array, 1197148 m^2, against the surface area of the receiver, 1513.9 m^2 [7].

4.3184e+05	6.0900e+05	6.9442e+05	7.4266e+05	7.7034e+05	7.7034e+05	7.7746e+05	7.7193e+05	7.6006e+05	7.3871e+05	6.9758e+05	6.2798e+05	5.0618e+05	2.4439e+05
4.1839e+05	5.9318e+05	6.7781e+05	7.2684e+05	7.5611e+05	7.5769e+05	7.6481e+05	7.6323e+05	7.4662e+05	7.2526e+05	6.8730e+05	6.2403e+05	5.0855e+05	2.5625e+05
4.1681e+05	5.9160e+05	6.7702e+05	7.2605e+05	7.5532e+05	7.6243e+05	7.6955e+05	7.6718e+05	7.4424e+05	7.2052e+05	6.8176e+05	6.1454e+05	4.9353e+05	2.4123e+05
3.7884e+05	5.5917e+05	6.5171e+05	7.0628e+05	7.3871e+05	7.3238e+05	7.3950e+05	7.3792e+05	7.4662e+05	7.2368e+05	6.8413e+05	6.1849e+05	5.0618e+05	2.6891e+05
4.5319e+05	6.1137e+05	6.9125e+05	7.3713e+05	7.6402e+05	7.7272e+05	7.7746e+05	7.7351e+05	7.4187e+05	7.1735e+05	6.7069e+05	5.9714e+05	4.7613e+05	2.3964e+05
3.8675e+05	5.5917e+05	6.4696e+05	6.9837e+05	7.2843e+05	7.2843e+05	7.3871e+05	7.3871e+05	6.7702e+05	6.5883e+05	6.2719e+05	5.6945e+05	4.5873e+05	2.2620e+05
4.1048e+05	5.7578e+05	6.6041e+05	7.1103e+05	7.4029e+05	7.4029e+05	7.4899e+05	7.4741e+05	7.3238e+05	7.1419e+05	6.8176e+05	6.2482e+05	5.1884e+05	2.9184e+05

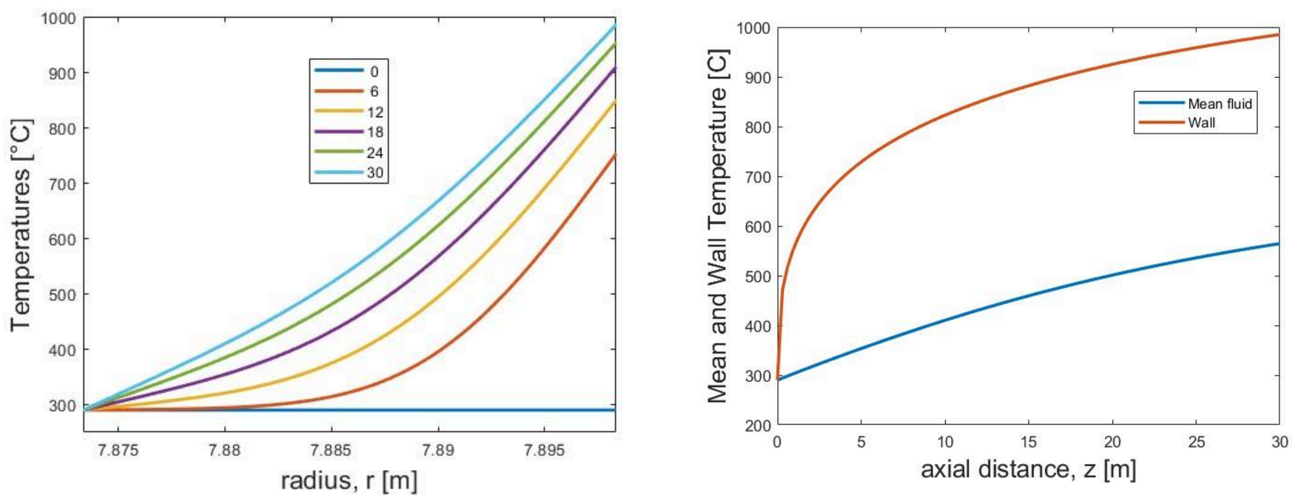
Table 1: Processed DNI with Surface Areas to show Heat Flux [w/m^2] into Receiver for 6/1/23 - 6/7/23.

For the mode of conduction, a 3D flow simulation in SolidWorks will be conducted as the salt flows past the irradiated receiver surface. The irradiated surface will be considered as one dimensional as the solar flux should be relatively uniform. Minor heat losses from radiation and convection on the sides and back of the receiver (tube/shell wall) will be accounted for, and the backing of the tube panel is heavily insulated and will be assumed to be adiabatic, so the only forms of heat transfer are from the receiver (tube wall) to the molten salt, as well as radiative and convective losses to the environment. With respect to the radiative heat flux from the solar energy, the value will be assumed to be constant for the one dimensional model (radial), and variable with respect to time. Both steady state and transient models will be constructed because the CST plants are assumed to be running under similar conditions for the duration of their operable period, with transient effects considered as the condition in terms of weather, which could change throughout the time period considered, and this will be compared against a steady state model to determine if significant fluctuations are present.

The validation plan is defined by comparing experimental and benchmark data for CST plants, where the temperature profile that is found from the model will be compared to multiple data sources found on CST plants. Another metric that needs to be validated is the heat transfer with regards to the molten salt flow through the pipe. SolidWorks Flow Simulation will be utilized as a commercial software to aid in constructing and validating the MATLAB steady state and transient models. The heat flux to the receiver will also be validated from researched sources found within available publications as well as the modeled panel temperatures for the receiver. Considering additional metrics that will be validated, the mean temperature of the molten salt with steady state and transient conditions will be validated by the data from CST plants that provide reports of the properties of the molten salt, as well as inlet and outlet temperatures at the receiver. Lastly, the energy efficiency will be correlated to multiple data sources to quantify the accuracy in performance data. If required for a secondary validation of any of the previous metrics, an analytical approach to verify the model behaves as expected as well as applying hand calculations for certain constraints will be implemented.

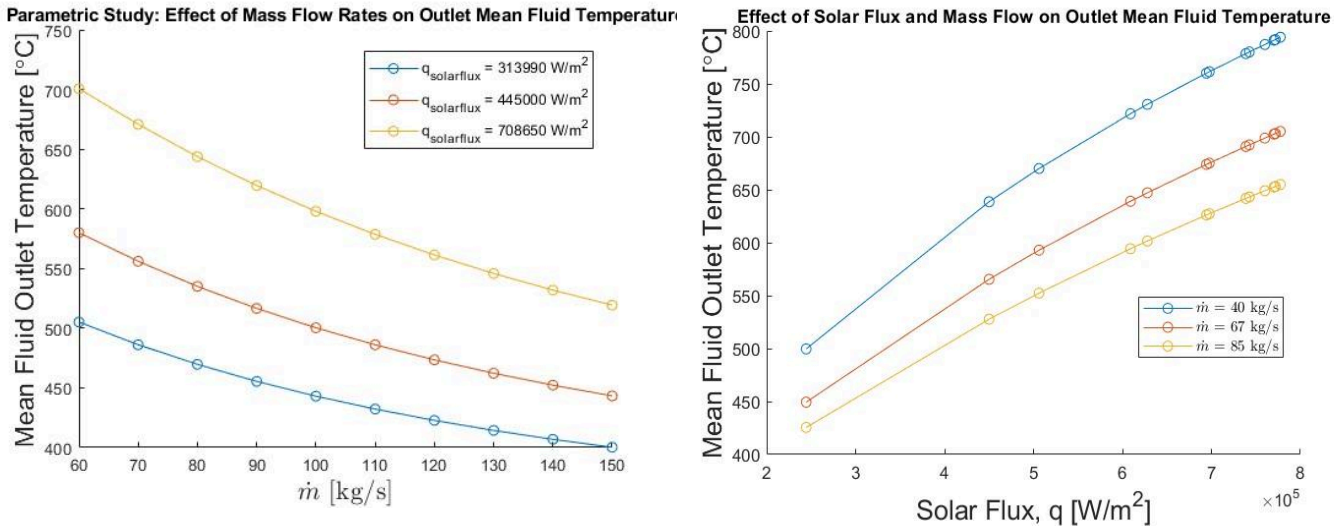
Modeling Results

The Steady State model constructed in MATLAB demonstrated an average flux of 445 kW/m^2 at the wall to achieve an outlet mean temperature of 565 degrees Celsius with an inlet mean temperature of 290 degrees Celsius. The mass flow rate for the molten salt within the shell was 67 kg/s based on the Crescent Dunes facility data from sources [1]. **Figure 2a** shows the temperature at set values in the radial direction throughout the flow in the axial direction. **Figure 2b** demonstrates the vastly different changes in wall temperatures along the pipe compared to the mean fluid temperature.



Figures 2a & 2b: Radial Temperature Profile for the Salt at Varying Heights, Mean and Wall Temperatures along the Pipe.

Parametric Studies were completed with the steady state model considering different geometries and properties. Utilizing the NREL NSRDB data throughout a 14 hour span, the mean outlet temperature was plotted versus the DNI data, which was used to determine the solar fluxes [7]. Differing mass flow rates were also used to determine the impact of both conditions on temperature. **Figure 3a** and **3b** both illustrate the parametric study based on varying mass flow rate and solar flux. Other parameters were investigated, including the wind speed and the receiver height at various conditions of mass flow rate and solar flux into the receiver. These figures are provided in the Appendix, labelled as **Figure A1** to **A2**, respectively. Finally, the last parametric study was completed with regards to the thermal efficiency of the receiver as the solar flux changed, which is provided in **Figure 4**.



Figures 3a & 3b: Effect of Mass Flow Rate on Mean Outlet Temperature, Effect of Solar Flux on Mean Outlet Temperature.

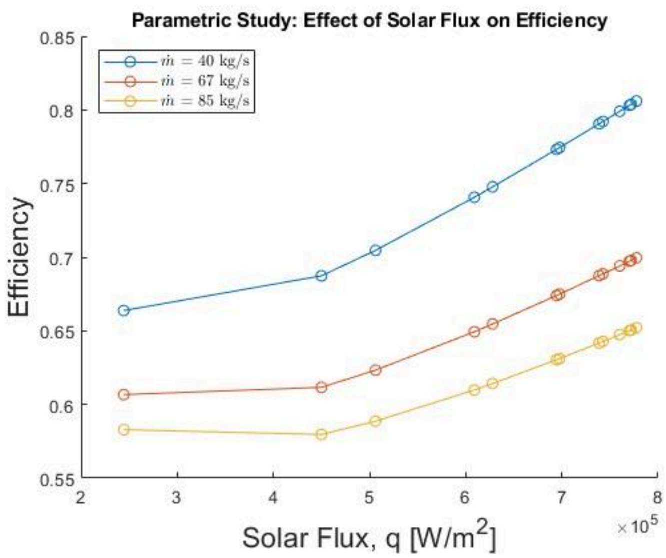


Figure 4: Effect of Solar Flux on Thermal Efficiency.

Using a 3D SolidWorks model of the receiver annulus geometry, a parametric study was performed with SolidWorks Flow Simulation. The study was performed by assuming a constant, uniform heat flux on the outer wall of the receiver, which changed with time. A study was performed for each hour of daylight using solar radiation data from the NREL NSRDB to determine the appropriate solar flux on the receiver over the course of a day. The simulation model included natural convection, and radiative heat losses to increase the accuracy of the results. The necessary mass flow rates dependent on the given DNI to ensure a mean outlet temperature of 565 degrees Celsius with a mean inlet temperature at 290 Celsius can be seen in the graphs below. Figure 3 compares the required mass flow rate with the incident solar flux on the side of the receiver, and as seen in the graph, this relationship is relatively linear. Figure 4 compares the required heat flux for standard operation against the hours since sunrise, which accounts for the hours of 6am - 8pm approximately.

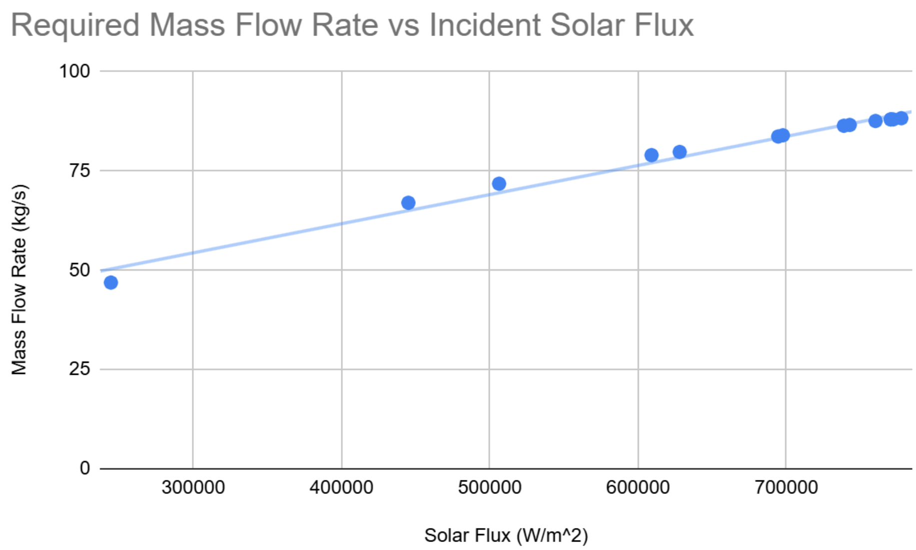


Figure 3: Required Salt Mass Flow Rate vs Solar Heat Flux

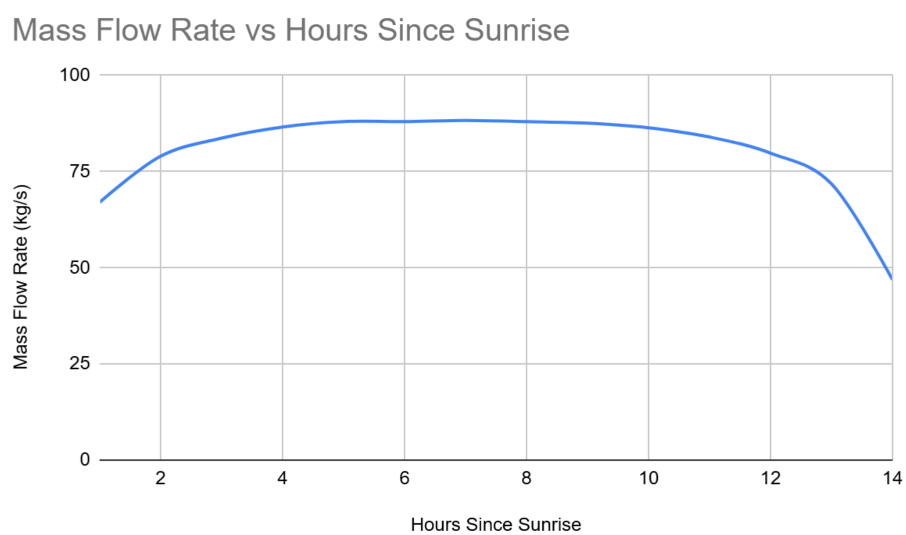


Figure 4: Required Salt Mass Flow Rate vs Hours Since Sunrise

Discussion

The MATLAB parametric studies yielded insight into the relationships between receiver area, natural convection, mass flow rate, and solar flux. It is evident that a lower mass flow rate correlates to a reduced radial velocity profile as the axial area of the annulus never changes. From **Figure A2**, it becomes apparent that lower mass flows require less axial distance to reach the desired output temperature under *constant* flux. With the calculated 445 kW/m^2 average flux, this figure highlights that the optimum receiver height lies below 30.5 m as convective effects begin to impact the flow. As the receiver height increases, more area is available for incident solar irradiation (assuming the heliostat array is increased in size) and natural convection. This figure illustrates that higher fluxes exhibit superior performance with increased areas, while lower fluxes struggle to balance out the natural convective heat losses. In other words, given expected mass flows and solar fluxes, there is an optimal upper limit to the receiver height. **Figures 3a** and **3b** demonstrate a relationship between solar flux and mass flow rates that outline that an increase in solar flux results in an increase in mean temperature while an increase in mass flow rate decreases the temperature profile. Combining these two parameters is a fantastic way to keep the receiver at the required temperature without driving a component towards a condition of overheating. **Figure 4** shows a relation of solar flux and efficiency that is also affected by the mass flow rates of the salt. Looking deeper, it can be seen that a high solar flux will result in a higher efficiency, but also the potential for failure due to the copper tubing reaching a state where it is unable to transfer all of the heat due to its thermal conductivity at a certain point.

Considering the MATLAB model and the Solidworks Flow Simulation model, results were largely similar in magnitude with some differences in specific values. The MATLAB model was only developed with respect to a steady state condition, and the transient condition was studied through utilizing various fluxes that were studied within parametric studies showing the heat transfer throughout the day and its relationship with the mass flow rate of the molten salt. The MATLAB model also provided a look at the mean temperature of the molten salt at values throughout the simplified pipe flow in the radial direction at specified points along the z-axis, which allowed for comparison against the Solidworks Flow Simulation model. Currently, a parabolic output for mean temperature with respect to z is constructed by the MATLAB model, while the Flow Simulator model is largely linear, which will likely require adjustment on one end or the other in accordance with which assumption is made going forward. The values between the two models are largely similar, with both ranging from 290 C to 565 C, with slight variation in the slopes along the axial direction. It was determined from the MATLAB model that an incident solar irradiation of 445 kW/m^2 was necessary to satisfy the output boundary condition under a mass flow rate of 67 kg/s. Similarly, the SolidWorks Flow Simulation model yielded an average value of around 450 kW/m^2 along the length of the receiver. The values are of similar magnitudes and overall values, but likely represent required continued fine tuning for an exact and finalized model. Looking towards the final state for the MATLAB model, continued development can occur to allow for analysis of differing weather conditions on the heat flux to the salt, and impacts on the ideal case, as well as alterations to the theoretical tube size and the respective impact of the heat transfer to the molten salt.

Considering validation of the MATLAB model without utilizing the Solidworks Flow Simulation, the NREL NSRDB source that provided accurate data on the DNI at the facility [7]. The value of 445 kW/m^2 seemed to agree with the average value throughout a 14 hour span during the month of June, 2023 [7]. This provided validation of the solar flux into the receiver, that would make the 2D model successful. The parametric studies required an external source for validation, which was pulled from an article found within the Science Direct catalog performing parametric studies on the CST plants [5]. The studies completed within this article were utilizing different geometries, but follow the same trend of parametric studies. All of the parametric studies performed in the 2D steady state MATLAB model followed the same trends for the corresponding study done [5]. Many of the values provided results around the same magnitude for the comparison studies, validating the completed studies [5].

Conclusion

In modelling the receiver of a Concentrated Solar Thermal plant, students gained a deeper understanding of the complex energy balance involved in warming molten salt for the purpose of energy transfer and production. Although certain aspects of heat transfer were neglected, such as axial conduction within the thermal medium, extensive investigation into the irradiation and natural convection provided a reasonable estimate of the thermal energy balance at the exterior surface. A steady state approach was utilized, assuming that the material properties and thermal storage would not change with time. Through this somewhat simplified, yet comprehensive approach, values for a numerical model were found to be in agreement with data produced using SolidWorks Flow Simulation. However, moving forward, modelling transient conditions would be the most applicable method to make comparisons to the SolidWorks flow simulations. This would likely be in the form of a 1D transient model that neglects radial components and discretizes along the receiver height in increments of dz. In terms of the steady state model, changing the material properties of the tubing would be done in a parametric study to find the best potential material that has the highest thermal efficiency. Another productive study in the steady state regime would be to alter the coating properties of the outside of the annulus to get a more in depth study on absorptivity and emissivity effects on the efficiency and the temperature profile. The tube wall thickness is an additional case that could be considered in order to optimize the material costs and time. While there is always room for continuous improvement, the completed studies provided a holistic approach and data set with respect to the functionality of the modeled CST facility, and a greater grasp on the technology and heat transfer considerations at hand.

Appendix

[1] Sarada Kuravi, Jamie Trahan, D. Yogi Goswami, Muhammad M. Rahman, Elias K. Stefanakos, “Thermal energy storage technologies and systems for concentrating solar power plants”, *Progress in Energy and Combustion Science*, Volume 39, Issue 4, Pages 285-319, 2013, ISSN 0360-1285, (https://doi.org/10.1016/j.pecs.2013.02.001.), (https://www.sciencedirect.com/science/article/pii/S0360128513000026)

[2] Hussein Ibrahim, Adrian Ilinca, Ahmed Faheem Zobaa, “Techno-Economic Analysis of Different Energy Storage Technologies”, *Energy Storage*, Chapter 1, 2013, (https://doi.org/10.5772/52220)

[3] D. Kearney, U. Herrmann, P. Nava, B. Kelly, R. Mahoney, J. Pacheco, R. Cable, N. Potrovitza, D. Blake, H. Price, “Assessment of a Molten Salt Heat Transfer Fluid in a Parabolic Trough Solar Field”, *J. Sol. Energy Eng.*, Pages 170-176, May 2003, (https://asmedigitalcollection.asme.org/solarenergyengineering/article/125/2/170/441078/Assessment-of-a-Molten-Salt-Heat-Transfer-Fluid-in)

[4] Edouard González-Roubaud, David Pérez-Osorio, Cristina Prieto, “Review of commercial thermal energy storage in concentrated solar power plants: Steam vs. molten salts”, *Renewable and Sustainable Energy Reviews*, Volume 80, Pages 133-148, 2017, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2017.05.084. (https://www.sciencedirect.com/science/article/pii/S1364032117307244)

[5] Q. Yu, P. Fu, and Y. Yang, "Modeling and parametric study of molten salt receiver of concentrating solar power tower plant," *Energy*, vol. 200, p. 117442, 2020. doi: 10.1016/j.energy.2020.117442.

[6] National Renewable Energy Laboratory. (n.d.). *NSRDB*. NSRDB - National Solar Radiation Database. https://nsrdb.nrel.gov/data-viewer

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[8] Wenjin Ding, Thomas Bauer, “Progress in Research and Development of Molten Chloride Salt Technology for Next Generation Concentrated Solar Power Plants,” *Engineering*, Volume 7, Issue 3, 2021, Pages 334-347, ISSN 2095-8099, https://doi.org/10.1016/j.eng.2020.06.027. (https://www.sciencedirect.com/science/article/pii/S2095809921000473)

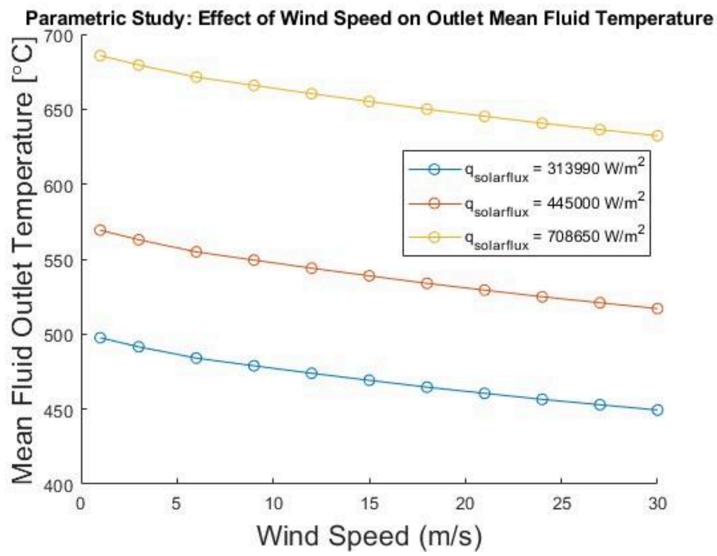
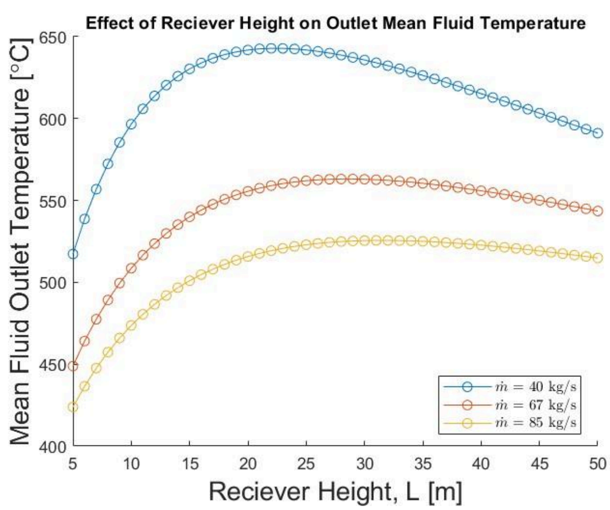
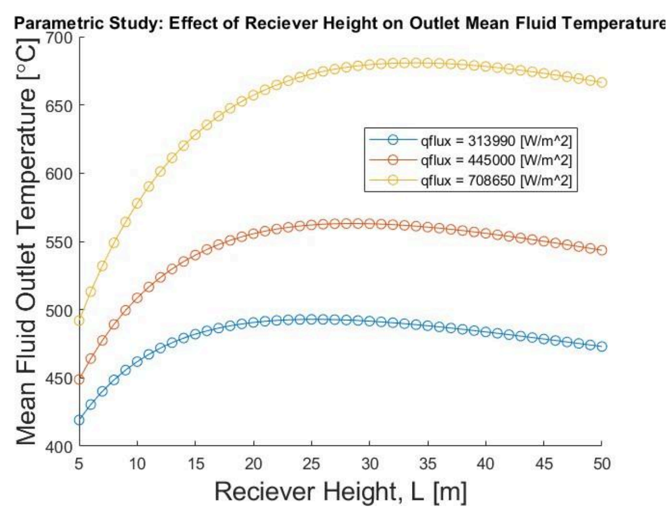


Figure A1: Effect of Wind Speed on Mean Outlet Temperature





Figures A2 & A3: Effect of Receiver Height on Mean Outlet Temperature varying Mass Flow Rate or Solar Flux.