Numerical study of natural convection in flat receiver with and without secondary reflector for solar parabolic dish system

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Abstract. The sustainability of our eco system is under threat due to frequent use of the fossil fuels. Due to the rapid depletion of the conventional energy sources and oil crisis, there is a great shift towards renewable energy sources. In the realm of renewable sources of energy, solar energy plays an impeccable role because of its abundance and dominance over the other sources. Therefore, efforts are being made to replace our existing conventional fuels with renewable energy sources. In this context, flow simulation and heat transfer are performed for the flat receiver with and without secondary reflector of solar parabolic dish collector is presented. A two-dimensional (2-D) model is used to investigate the approximate estimation of the natural convection heat loss from the actual geometry of the receiver for solar dish concentrator system. The Nusselt number correlations are proposed separately and compared for both receiver with secondary reflector (WSR) and without secondary reflector (WOSR) using power law and asymptotic computational fluid dynamics technique.

Keywords: Numerical analysis; Flat receiver; Secondary Reflector; Solar Parabolic Dish Collector; Nusselt number; Natural convection; ACFD.

1. Introduction
The issue of renewable energy is becoming significant due to increase in power demand instability of the oil crisis and environmental problems. Among all the available renewable energy sources, solar energy is the most abundant, dominant, powerful and efficient energy source. Solar energy can be utilized for the applications of heat as well as for the generation of electricity. Concentrating solar system is the current trending approach for co-generation of heat and electricity. In this regard, Reddy et al. [1] examined the thermal performance of 20m² fuzzy solar dish collector and determined the solar dish focal image characteristics to propose the appropriate receiver design. Initially, the theoretical investigations on the dish with customized cavity receiver were performed at different operating conditions and estimated the total heat loss. Later, the real time investigation on the dish with customized cavity receiver was performed based on time constant, stagnation test and daily performance test. The investigation resulted that the efficiency was augmented with rise of volume flow rate. Sendhil Kumar et al. [2] numerically studied the natural convective heat loss for three different receivers of a solar parabolic dish concentrator system. Among those three receivers; the customized cavity receiver was the suggested...
receiver for a solar dish collector system of fuzzy focal type. Ravi Kumar et al. [3] numerically analysed the 3-D porous line receiver for solar parabolic trough concentrator system and also investigated the effect of receiver design, thermal fluid properties and solar radiation on total heat collection by using renormalization-group (RNG) k-ε turbulent model with Therminol-VP1 as working fluid. The parametric investigation on the receiver resulted that the usage of porous medium in tubular receiver increases the system performance of system. Sendhil Kumar et al. [4] numerically studied the solar radiation and natural convection heat transfer in a cavity of trapezoidal shape absorber for Compact Linear Fresnel Reflector by using CFD FLUENT 6.3 and related with other cavity of closed model for validation. The simulation outcome was presented as correlation of Nusselt number to depict the consequence of the parameters on surface radiation and Natural convection. Reddy et al. [5,6] numerically studied about the 2-D surface radiation heat transfer and combined natural convection in a customized cavity receiver of parabolic dish concentrator system for investigating the consequence of the operating temperature, orientation, surface emissivity and the geometry on the overall heat loss originating at receiver and resulted that the convective heat loss was affected by receiver inclination whereas the radiation heat loss was affected by surface properties. The outcome of the current analysis was in good accord with models of open cavity. Sendhil Kumar et al. [7] developed and evaluated the performance of double axis tracking system for solar parabolic dish system. A 1-Watt photovoltaic panel was kept at focal point to evaluate the open circuit and short circuit voltage and resulted that the recommended system augmented short circuit current of 0.11A by 86.0%. Henceforth, it was concluded that the proposed system can be used only in parabolic system with concentrating photovoltaic module as a focal point for future researches. Reddy et al. [8] numerically studied the performance of the solar parabolic trough concentrator receiver by considering the various porous receiver geometries. The heat transfer and internal flow analysis was performed based on an RNG k-ε turbulent model, whereas foreign heat losses are considered as a laminar natural convection model and was solved using FLUENT. The results of the current analysis were in good accord with all other open cavity models and a comparative study was depicted for several porous geometries to get an optimum energy efficient receiver configuration. Sendhil Kumar et al. [9] numerically analyzed the 3-D solar dish customized cavity receiver with CPC, Trumpet and Cone reflectors for convective and radiative heat loss against the receiver for several operating temperatures and angles of inclination. The results depicted that trumpet shaped reflector on the receiver has given better performance when compared with the remaining designs. Sendhil Kumar et al. [10] numerically investigated the 2-D customized cavity receiver of solar parabolic dish concentrator system to evaluate the natural convection heat loss for both designs “without insulation” (WOI) and “with insulation” (WI) at the receiver and by varying inclination angles. The maximum heat loss through convection was observed during 0° inclination for both without and with insulation cases. The results of the current analysis were in good accord with other cavity models of open type. Sendhil Kumar et al. [11] numerically studied natural convection heat loss and radiation from a customized cavity receiver of solar parabolic dish of different inclination angles by using a trending approach i.e., Asymptotic Computational Fluid Dynamics (ACFD). individual Nusselt number correlations for heat loss through natural convection and combined heat loss through radiation and convection were given. It was noticed that the current heat loss model adheres to the same trend as of the other heat loss models. In this current article, the ACFD approach is utilized to advance a model with steady-state laminar natural convective correlation of Nusselt number for flat receiver without and with secondary reflector of a solar parabolic dish collector system.

2. Numerical modelling of flat receiver with and without secondary reflector

2.1. Mathematical Modelling

The receiver position is at the focal point of the parabolic dish collector. In real case the receiver is 3-dimensional in nature and it is approximated to 2-dimensional for simplicity. The receiver consists of water, which is considered to have identical temperature as of the surface. The simulations of heat transfer have been carried out depending on the concurrent outcome of system of the equations
portraying the conservation of energy, momentum and mass. The vector form of the energy equations momentum, and continuity.

1. Equation for Momentum:
   \[ q \cdot \nabla \mathbf{q} = \nabla \cdot \left( \frac{\mathbf{v} P}{\rho} + \mathbf{v} \nabla \mathbf{q} \right) \] (1)

2. Equation for Energy:
   \[ \nabla \cdot \left( k \nabla T \right) = \rho \frac{DH}{dt} - \frac{DP}{dt} \] (2)

3. Equation for Continuity:
   \[ \nabla \cdot \mathbf{q} = 0 \] (3)

The two-dimensional modelling and generation of grids have been carried out using ANSYS 19.1 R1 package. In real case, the flat receiver with and without secondary reflector are bounded by an infinite atmosphere. a rectangular enclosure (outer domain) is made such that the receiver with and without secondary reflector is placed centrally to attain such infinite atmosphere in numerical work. The dimensions of the rectangular arena should get enlarged until it has no significant outcome on the heat flow and operating fluid inside the receiver. The Grid independent analysis of the receiver is performed with and without secondary reflector on it, to acquire optimum cells. The region inside the cavity is given as fine grid and a coarse grid is maintained in the outer domain. At the end, overall number of optimum cells obtained are 47,816.

2.2. Boundary Conditions

The receiver’s geometry had been set to several boundary conditions that prevails in the actual environment. The receiver’s surface is constantly subjected to the solar insolation. Due to this, the surface area may achieve a constant isothermal state at the stagnation condition. Hence, the isothermal boundary condition has been applied to surfaces. The governing equations are based on energy conservation, momentum and continuity. The steady 2-Dimensional, state and laminar governing equations are elucidated using ANSYS FLUENT 19.1 by incorporating an implicit solver. For the velocity coupling and pressure, COUPLED algorithm was used. The discretization of energy and momentum had been performed using first order upwind scheme. The pressure was discretized by using body force weighted criteria. The criteria for minimum convergence were fixed at $10^{-6}$ for energy and $10^{-3}$ for velocity and continuity. To acquire the heat transfer and flow outcomes, the software commences the iteration till the principle of convergence is fulfilled. The working fluid properties are given based on the mean value of ambient air and receiver’s surface temperature.

![Temperature contour of receiver with bottom surface at 100°C and 300°C](image)

**Figure 1.** Temperature contour of receiver with bottom surface at 100°C and 300°C

For 100°C, Grashof number (Gr)=1.5057×10^8, Rayleigh number (Ra)=1.5057×10^8, Nusselt number (Nu)=240.75, Heat transfer coefficient(h)=38.202 W/m²-k and for 300°C, Grashof number (Gr)=9.03×10^7, Rayleigh number (Ra)=6.15×10^7, Nusselt number (Nu)=217.65, Heat transfer coefficient(h)=44.015 W/m²-k.
For 220°C, Grashof number (Gr)=1.262×10^8, Rayleigh number (Ra)=0.866×10^8, Nusselt number (Nu)=231.365, Heat transfer coefficient(h)=42.417 W/m^2-k and for 550°C, Grashof number (Gr)=3.956×10^7, Rayleigh number (Ra)=2.66×10^7, Nusselt number (Nu)=139.931, Heat transfer coefficient(h)=35.216 W/m^2-k.

2.3. Validation of the natural convection model

The present geometry - Flat receiver with and without secondary reflector is relatively new and obscure. Therefore, the numerical simulation procedure was justified with natural convection model with a square cavity and also compared with the available literature. For validating the current numerical method of flat reciever, a classic case of natural convection in square cavity discussed by De Vahl Davis et al. [12] had been taken into consideration. The problem had been studied experimentally and numerically under laminar and steady flow with use of water. The outcomes of numerical and experimental investigation were expressed in terms of Rayleigh and Nusselt number correlations: Nu=2.56(Ra)^0.25 explicitly. With the help of this numerical method, the Nusselt number was estimated. The similarity between our current numerical study with De Vahl Davis’s study is adorned in the table below. It is perceived that our numerical method is acceptable, when it is compared with available experimental data.

| S.no | Rayleigh number (Ra) | Nusselt number (Nu) | Nusselt number (Nu) | Our study | Present | Deviation in Percentage (%) |
|------|----------------------|---------------------|---------------------|-----------|---------|-----------------------------|
|      |                      | NuExp               | NuNum               | Nu        | NuNum   |                             |
| 1    | 1.04×10^8            | 258.52              | 285.78              | 240.75    | 240.75  | -6.87                       |
| 2    | 4.57×10^7            | 210.48              | 232.68              | 197.98    | 197.98  | -5.93                       |

3. Results and Discussion

3.1. Nusselt number correlation developed by power law for flat receiver

By using the heat transfer coefficients values obtained from the numerical simulation Rayleigh number and Nusselt number are calculated for 22 data points. The 2-dimensional Natural convective Nusselt number relation for flat receiver is expressed as

\[ \text{Nu} \approx 2.0462(Ra)^{0.2586} \text{ for } 10^7 \leq Ra \leq 10^8 \]

The above relation is obtained by fitting Nu vs Ra curve into power law in Axum software. The exactness of the fit is indicated by the R-square coefficient which is 0.986.
3.2. **Nusselt number correlation developed by power law for flat receiver with secondary reflector**

The 2-Dimensional Natural convective Nusselt number correlation for flat receiver with secondary reflector is expressed as

\[ \text{Nu (WSR)} = 0.1(Ra)^{0.42}, 10^7 \leq Ra < 10^8 \] (4)

The above relation is obtained by fitting Nu vs Ra curve into power law in Axum software. The exactness of the fit is indicated by the R-square coefficient which is 0.984.

3.3. **Nusselt number correlation developed by Asymptotic Computational Fluid Dynamics Technique**

In the problem with Natural Convection, the Nusselt number is a function of Rayleigh number. In accordance with the self-reliant variables, the conduct of natural convection in flat receiver can be designed by developing a Nusselt number correlation. The Natural Convective Nusselt number correlation can be designed by ACFD method. The usage of ACFD technique considerably decreases the number of data points required for attaining the authentic correlation. The effect of self-reliant variable is designed to figure out the correlation physical nature.

3.3.1. **Nusselt number correlation for flat receiver:** To evolve a correlation in ACFD technique, the median of a parameter was taken as reference to evolve correlations. Thus, \( R_{a_{ref}} = 5.92 \times 10^7 \). In the present investigation, Rayleigh number is studied in a range of \( 10^6 - 10^7 \). A linearized curve is achieved for the \( (Ra/R_{a_{ref}})^{0.21} \) with respect to Rayleigh number. Obtaining the proper exponent of 0.21 is one of
the eminent methods in the ACFD approach. It is a trial and error method for obtaining a linear relationship between ratio of the Ra and Nu. The correlation coefficient obtained is 0.992.

\[ \text{Figure 7. Nu vs Ra ratio raised to power 0.21 for flat receiver} \]

\[ \text{Figure 8. Deviation of Natural Convective Nusselt number with Rayleigh number of the flat receiver} \]

The common form of Natural Convective Nusselt number correlation for flat receiver by ACFD technique is expressed as:

\[ \text{Nu} = \text{Nu}_{\text{ref}} + (\varphi_1 - \varphi_1, \text{ref}) \frac{\partial \text{Nu}}{\partial \varphi_1} \]  
(5)

Where \( \varphi_1 = \frac{\text{Ra}}{\text{Ra}_{\text{ref}}} \)^{0.21}

The coefficient \( \frac{\partial \text{Nu}}{\partial \varphi_1} \) is evaluated by achieving the result to the governing equations with all but one parameter fixed at the reference value.

The convective number correlation thus obtained for flat receiver is given by \( \text{Nu} = 214.5 + (\varphi_1 - 1)247 \).

The correlation obtained gives us the acceptable results with minimum error.

\[ \text{Figure 9. Deviation of Natural convective Nusselt number with self-reliant variable of the flat receiver} \]

3.3.2 Nusselt number correlation by ACFD for flat receiver with secondary reflector: To evolve a correlation in ACFD technique, the median of a parameter was taken as reference to evolve correlations. Thus, \( \text{Ra}_{\text{ref}} = 5.66 \times 10^7 \). in the present investigation, Rayleigh number is studied in a range of \( 10^6 - 10^7 \).

A linearized curve is achieved for the \( (\text{Ra}/\text{Ra}_{\text{ref}})^{0.3} \) with respect to Rayleigh number. Obtaining the proper
exponent of 0.3 is one of the eminent methods in the ACFD approach. It is a trial and error method for obtaining a linear relationship between Nu and ratio of Ra. The correlation coefficient obtained is 0.977.

![Figure 10. Nu vs Ra ratio raised to power 0.3 for flat receiver with secondary reflector](image1)

![Figure 11. Deviation of Natural convective Nusselt number with Rayleigh number of flat receivers with secondary reflector](image2)

The general form of Natural Convective Nusselt number correlation for flat receiver is expressed as:

$$\text{Nu} = \text{Nu}_{\text{ref}} + (\theta_1 - \theta_{1, \text{ref}}) \frac{\partial \text{Nu}}{\partial \theta_1}$$  \hspace{1cm} (6)

Where $\theta_1 = [\text{Ra}/\text{Ra}_{\text{ref}}]^{0.3}$

The Natural convective number correlation thus obtained for flat receiver with secondary reflector is given by $\text{Nu} = 184.5 + (\theta_1 - 1)442.21$. The correlation obtained gives us the acceptable results with minimum error.

![Figure 12. Deviation of Natural convective Nusselt number with self-reliant variable of flat receiver with secondary reflector](image3)
4. COMPARISON OF NUSSELT NUMBER CORRELATIONS

4.1. ACFD vs Power law Nusselt Number for flat plate receiver

In the above graph the Nusselt number varies from 171.21 to 240.75 for power law and from 127.08 to 240.75 for ACFD technique.

In the above graph the Rayleigh number varies from $2.72 \times 10^7$ to $1.046 \times 10^8$ for power law and ACFD technique.

It shows that convective Nusselt number obtained by adopting power law procedure and convective Nusselt number obtained by ACFD are comparable. The maximum difference between correlation developed by power law and ACFD Technique is obtained as 6.83% for both used and non-used data points.

4.2. ACFD vs Power law Nusselt Number for flat plate receiver with secondary reflector

In the above graph the Nusselt number varies from 139.931 to 231.365 for power law and from 140 to 231 for ACFD technique.

In the above graph the Rayleigh number varies from $2.67 \times 10^7$ to $8.66 \times 10^7$ for power law and ACFD technique. It shows that convective Nusselt number obtained by adopting power law procedure and convective Nusselt number obtained by ACFD are comparable. The maximum
difference between correlation developed by power law and ACFD Technique is obtained as 9.71% for both non-used and used data points.

5. Conclusions
The results of 2-Dimensional numerical analysis were reported in terms of Nusselt number correlations for flat receiver without and with secondary reflector. The correlations are obtained by both power law and ACFD technique. It is found that the difference between the convective Nusselt numbers developed by power law and ACFD technique were found to be 6.83% for flat receiver and 9.71% for flat receiver with secondary reflector. It is also found that the number of data points needed were reduced considerably with the use of ACFD technique and also reasonably accurate Nusselt number correlation is obtained. The well-known benchmark model is compared with present numerical model. The correlation developed may effectively be used to measure the natural convective losses from the flat receiver with and without secondary reflector of a solar parabolic concentrator system.

Nomenclature

| Symbol | Description       |
|--------|-------------------|
| Ra     | Rayleigh number   |
| ø      | independent variables |
| Gr     | Grashof number    |
| h      | heat transfer coefficient (W/m²-K) |
| T      | Temperature (K)   |
| t      | Time (s)          |
| ρ      | density (Kg/m³)   |
| P      | Pressure (N/m²)   |
| q      | Energy flux (W/m²) |
| Nu     | Nusselt number    |

Subscripts

| Subscript | Description       |
|-----------|-------------------|
| atm       | Atmospheric pressure |
| Exp       | Experimental      |
| Num       | Numerical         |
| ref       | Reference         |

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**Acknowledgement:**
The authors would like to acknowledge the Department of Science and Technology, India for the financial support under Young Scientist Scheme DST-SERB PROJECT NO: YSS/2014/000748. Also, we would like to thank Director of NIT-Puducherry for providing the computational facilities for this project.