# SIMULATION OF CONVECTIVE HEAT TRANSFER COEFFICIENT IN THE RECEIVER TUBE OF A PARABOLIC TROUGH CONCENTRATOR

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## Abstract

The evaluation of the convective heat transfer coefficient, $h_c$ by simulation can be made simple, if modelling of the temperature dependent parameters is carried out effectively. Usually Reynolds, Prandtl and Nusselt numbers are used to compute the convective heat transfer coefficient. The parameters defining these numbers are known to be dependent on temperature and the changes in these parameters with the change in temperature will be difficult to be accounted for, especially during a computer simulation process. A solution to overcome this problem is executed successfully by obtaining temperature dependent models. The method to calculate $h_c$ is based on the application of $R_{FACTOR}$, $K_{FACTOR}$ and also $H_{FACTOR}$; all three obtained by using the linear polynomial curve fitting method. The models are then used as part of a MATLAB program to evaluate $h_c$ of the working fluid flowing inside the circular cylindrical receiver tube of a parabolic trough concentrator.

## Introduction

The flow in a smooth tube can either be laminar or turbulent. The characteristic associated with the nature of the flow will definitely affect the convective heat transfer coefficient of the thermic fluid flowing in the tube. Although it is difficult to estimate the $h_c$ analytically, but if compared to the evaluation of heat transfer coefficient due to wind $h_w$, the process is more readily estimated, as the flow is confined within a certain shape of the tube. For a fixed surface area, the circular tube gives the most heat transfer with the least pressure drop. So in this study, although there is an empirical equation to calculate the hydraulic diameter of uncommon shapes of tubes, the focus here is on circular tubes. The study is divided into two parts, one concentrating on the laminar flow, while the other on turbulent flow. The nature of flow is determined by using a reliable indicator, popularly known as the Reynolds number, where the following information provided in Table 1 is used to identify the nature of flow.

It is also useful to know the nature of the flow, especially in evaluating the Nusselt number, which is used in the computation of the convective heat transfer coefficient, $h_c$. The computational analysis of $h_c$ inside these tubes can be considered as tedious, especially if it is carried out in an environment where the temperature changes significantly. One can obtain the standard values for the parameters defining $h_c$, but to a certain limit. This is due to the supplied data being recorded at certain temperature intervals only. The resolution of the data depends on these temperature intervals.

| | |
|---|---|
| Re < 2300 | Laminar flow |
| 2300 ≤ Re ≤ 4000 | Transition from laminar to turbulent flow |
| Re > 4000 | Turbulent flow |

***Table 1:*** *Indicators to classify the nature of fluid flowing in smooth tubes.*

## Theory

Reynolds, Prandtl and Nusselt numbers are normally used to compute $\boldsymbol{h_c}$. The properties of the parameters defining these numbers are also known to be dependent on temperature and for the evaluation of $\boldsymbol{h_c}$ by simulation; a large database of physical properties of these parameters is needed. The exact temperature at which a certain evaluation is to be carried out will not be possible. One quick and simple solution is to build temperature dependent models. The general popular correlation for obtaining the convective heat transfer coefficient is shown in Eq. (1) and the evaluation of the Nusselt number for a turbulent flow is given as Eq. (2)[1].

$$h_c = \frac{Nu\,k}{D_i} \tag{1}$$

$$Nu = 0.023\,Re^{0.8}\,Pr^{0.4} \tag{2}$$

Eq. (1) relates $\boldsymbol{h_c}$ to the Nusselt number $Nu$, the thermal conductivity $k$ of the fluid flowing in the tube and the inner diameter $D_i$ of the tube. However, Nusselt number is closely correlated to the Reynolds number $Re$ as well as the Prandtl number $Pr$.

Reynolds number can be evaluated using Eq. (3) below, depending on the mean flow velocity $V$, inner tube diameter $D_i$ and the kinematic viscosity $\nu$ of the working fluid;

$$\mathrm{Re} = \frac{VD_i}{\nu} \tag{3}$$

Prandlt number, used in Eq. (2) is given below as Eq. (4), where $\mu$ is the dynamic viscosity, $C_p$ and $k$ is the specific heat capacity and the thermal conductivity of the fluid flowing in the tube respectively.

$$\mathrm{Pr} = \frac{\mu C_p}{k} \tag{4}$$

## Methodology

Normally, the first number to be determined in a flow problem is the Reynolds number. The following Eq. (5) shows the dependency on temperature is incorporated into the standard Reynolds number by introducing a computer generated factor known as the $R_{FACTOR}$ [2];

$$\mathrm{Re} = \frac{VD_i}{\nu} = \frac{\rho VD_i}{\mu}$$

$$\mathrm{Re} = \left(\frac{14J}{11D_i}\right) \times \left(R_{FACTOR}\right)^{-1} \tag{5}$$

where $J$ is the mass flow rate of the working fluid. In the event that the $\mathrm{Re} < 2300$, the correlation to be used where the surface tube temperature is assumed to be constant is as follows[1];

$$Nu = 3.66 \tag{6}$$

The equation to calculate the convective heat transfer coefficient $\boldsymbol{h_c}$ based on Eq. (1) is made to depend on temperature by using the $K_{FACTOR}$.

$$h_c = \left(\frac{3.66}{D_i}\right) \times K_{FACTOR} \tag{7}$$

If $\mathrm{Re} \geq 2300$, then the flow is considered to be turbulent and the same equations as the turbulent flow can be used to estimate $\boldsymbol{h_c}$. The Nusselt number for flow of this nature is obtained by using the Dittus-Boulter's equation, which is shown in Eq. (2). The refined equation, with the incorporation of the mass flow rate $J$, is given as Eq. (8). It can be observed that $\boldsymbol{h_c}$ depends on the mass flow rate $J$, the tube's inner diameter $D_i$, specific heat capacity $C_p$, thermal conductivity $k$ and the dynamic viscosity $\mu$.

$$h_c = 0.028 \frac{J^{0.8} C_p^{0.4} k^{0.6}}{D_i^{1.8} \mu^{0.4}} \tag{8}$$

The parameters $C_p$, $k$ and $\mu$ are all temperature dependent, therefore the evaluation of $\boldsymbol{h_c}$ can be strenuous, as the values will vary with temperature as well. Therefore, in order to overcome this problem, the use of $H_{FACTOR}$ [3] is introduced. This new correlation is defined as Eq. (9) below;

$$H_{FACTOR} = \frac{C_p^{0.4} k^{0.6}}{\mu^{0.4}} \tag{9}$$

The method used to find the relationship between the parameters defining the $R_{FACTOR}$, $K_{FACTOR}$ *and* $H_{FACTOR}$ and their dependency on temperature is by using curve-fitting procedures with minimal error of less than 5%.

## Results

The evaluation of $R_{FACTOR}$, $K_{FACTOR}$ *and* $H_{FACTOR}$ depends on the type of thermic fluid used. In this study, unused engine oil as the working fluid is used and the curve fitting method that gave the best correlation for $R_{FACTOR}$, $K_{FACTOR}$ and $H_{FACTOR}$ with the lowest standard errors is the polynomial curve fit method and the general form is given as Eq. (10).

$$\begin{aligned} P = a + bT + cT^{2} + dT^{3} + eT^{4} + fT^{5} \\ + gT^{6} + hT^{7} + iT^{8} + jT^{9} + kT^{10} + lT^{11} \end{aligned} \tag{10}$$

The following Table 2 shows the coefficients that fit into Eq. (10) and used to evaluate the respective $R_{FACTOR}$, $K_{FACTOR}$ and $H_{FACTOR}$ at the operating temperatures. After all the parameters used to build the models are obtained, a MATLAB program was written to evaluate $\boldsymbol{h_c}$ inside the receiver tube of a parabolic trough concentrator where unused engine oil is used as the working fluid.

| Polynomial Fit Coefficients Data for Unused Engine Oil | | | |
|---|---|---|---|
| P / Coefficients | $R_{FACTOR}$ | $K_{FACTOR}$ | $H_{FACTOR}$ |
| a | 3.84999550E+00 | 1.47000470E-01 | 3.66059650E+00 |
| b | -3.33005230E-01 | -1.36782040E-03 | 1.43259090E-01 |
| c | 1.59929340E-02 | 2.26705010E-04 | 4.27541720E-04 |
| d | -5.50803560E-04 | -1.78951110E-05 | 6.01093940E-05 |
| e | 1.43289520E-05 | 8.14695780E-07 | -9.00923530E-07 |
| f | -2.76958070E-07 | -2.30604530E-08 | 5.22047110E-09 |
| g | 3.86362580E-09 | 4.19136010E-10 | -1.08269030E-11 |
| h | -3.78421950E-11 | -4.95778840E-12 | 0.0000000E+00 |
| I | 2.51836110E-13 | 3.79078230E-14 | 0.0000000E+00 |
| j | -1.07971990E-15 | -1.80570200E-16 | 0.0000000E+00 |
| k | 2.68288450E-18 | 4.87059040E-19 | 0.0000000E+00 |
| l | -2.93085480E-21 | -5.68152000E-22 | 0.0000000E+00 |

***Table 2:*** *Polynomial fit coefficient values to be used in Eq. (10) to obtain the temperature dependent equations for* $R_{FACTOR}$, $K_{FACTOR}$ *and* $H_{FACTOR}$.

The MATLAB program codes are shown in Table 3 and the results are shown in Fig. 1 below.

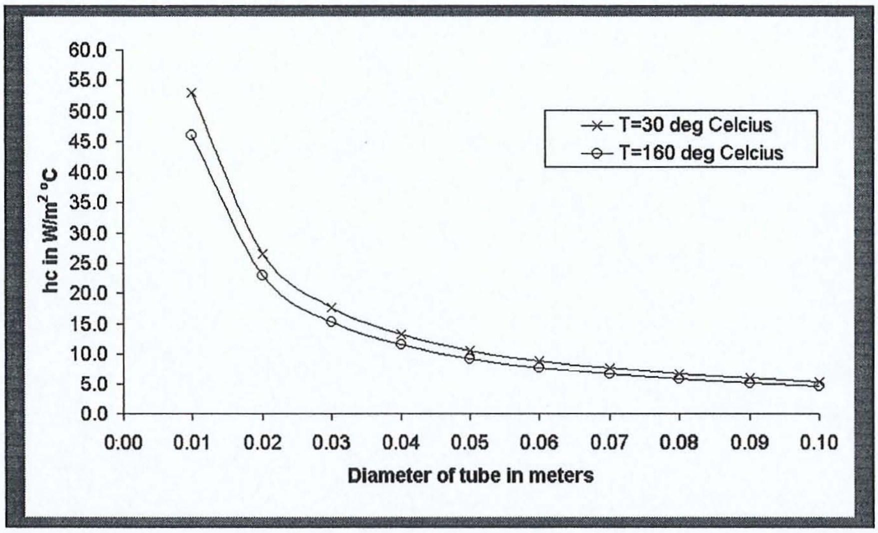


***Fig. 1**: Graph showing the variation in $h_c$ as the tube diameter is increased and the mass flow rate **J** is kept constant.*

Fig. 1 shows a significant drop of $h_c$ when the diameter is increased from 0.01 m to 0.02 m, clearly indicating that the nature of flow has changed, from turbulent to laminar. Simulation can be carried out repeatedly, by varying the other parameters, at any given temperature.

The simulation codes shown below may also be used together with other programs, to evaluate the heat removal factor and subsequently, the efficiency of the parabolic trough concentrator's design.

## Conclusion

By using this methodology to evaluate the convective heat transfer coefficient, the independence from evaluating the fluid properties at certain constant or continuously changing temperatures is achieved. There is no need to include physical properties database as close matching values for a given set of temperatures can be computed directly by extrapolation or interpolation, depending on the correlation factors. The extended flexibility to change some of the parabolic trough concentrator's design parameters and to run the simulation at any thought of temperature can ensure that a high thermal efficiency is obtained, with the right type of working fluid flowing through the receiver at a controlled flow rate, with optimum sized tube diameter.


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```
%Variables :
% J : mass flowrate in kg/s
J=0.01;
Di=0.01:0.01:0.1;
Tmi=30;

% Rfactor for engine oil

Ra=3.8499955;Rb=-0.33300523;
Rc=0.015992934;Rd=-0.00055080356;
Re=0.000014328952;Rf=-0.00000027695807;
Rg=0.0000000038636258;Rh=-0.000000000037842195;
Ri=0.00000000000025183611;Rj=-0.00000000000000010797199;
Rk=0.0000000000000000026828845;
Rl=-0.000000000000000000000029308548;
Rfactor=Ra+(Rb.*Tmi)+(Rc.*(Tmi.^2))+(Rd.*(Tmi.^3))+...
    (Re.*(Tmi.^4))+(Rf.*(Tmi.^5))+(Rg.*(Tmi.^6))+...
    (Rh.*(Tmi.^7))+(Ri.*(Tmi.^8))+(Rj.*(Tmi.^9))+...
    (Rk.*(Tmi.^10))+(Rl.*(Tmi.^11));
% Kfactor for engine oil
Ka=0.14700047;Kb=-0.0013678204;
Kc=0.00022670501;Kd=-0.000017895111;
Ke=0.00000081469578;Kf=-0.000000023060453;
Kg=0.00000000041913601;Kh=-0.0000000000049577884;
Ki=0.000000000000037907823;Kj=-0.0000000000000001805702;
Kk=0.00000000000000000048705904;
Kl=-0.0000000000000000000000568152;
Kfactor=Ka+(Kb.*Tmi)+(Kc.*(Tmi.^2))+(Kd.*(Tmi.^3))...
   +(Ke.*(Tmi.^4))+(Kf.*(Tmi.^5))+(Kg.*(Tmi.^6))...
   +(Kh.*(Tmi.^7))+(Ki.*(Tmi.^8))...
   +(Kj.*(Tmi.^9))+(Kk.*(Tmi.^10))+(Kl.*(Tmi.^11));
% Hfactor for engine oil
Ha=3.6605965;Hb=0.14325909;
Hc=0.00042754172;Hd=0.000060109394;
He=-0.00000090092353;Hf=0.0000000052204711;
Hg=-0.000000000010826903;Hh=0;Hi=0;Hj=0;Hk=0;
H=Ha+(Hb.*Tmi)+(Hc.*(Tmi.^2))+(Hd.*(Tmi.^3))+...
    (He.*(Tmi.^4))+(Hf.*(Tmi.^5))+(Hg.*(Tmi.^6))+...
    (Hh.*(Tmi.^7))+(Hi.*(Tmi.^8))+(Hj.*(Tmi.^9))+...
    (Hk.*(Tmi.^10));
% To check and see the nature of the flow : Reynolds Number
R1=((4.*J)./(pi.*Di.*Rfactor));
if R1<2300
Nu=3.66;
hf=((3.66.*Kfactor)./Di);
elseif R1>=2300
J1=J.^0.8;
D1=Di.^1.8;
hf=(0.028.*J1.*H)./D1;
end
% Output
q=[Di',hf']
```

***Table 3:** A MATLAB program to obtain* $h_c$.

## References


1. Yunus.A.Cengel, *Heat Transfer : A Practical Approach*, (USA : WCB/McGraw-Hill Series in Mechanical Engineering, 1998).

2. Balbir Singh and Fauziah Sulaiman, "$R_{FACTOR}$ To Determine The Reynolds Number Of Saturated Water Flowing In Tubes", *proceedings of the World Renewable Energy Congress 2002*, Cologne, Germany.

3. Balbir Singh and Fauziah Sulaiman, "$H_{FACTOR}$ To Determine The Convective Heat Transfer Coefficient Of Saturated Water Flowing In Tubes", Paper presented at *Persidangan Fizik*