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SIMULATION OF HEAT TRANSFER COEFFICIENT DUE TO WIND BLOWING ACROSS CYLINDRICAL RECEIVER OF A PARABOLIC TROUGH CONCENTRATOR

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Abstract

The evaluation of the heat transfer coefficient due to wind, $\boldsymbol{h_w}$ over certain surfaces can be considered as tedious, if it is carried out in an environment where the temperature changes significantly. Reynolds, Prandtl and Nusselt numbers are used to compute the wind heat transfer coefficient. The parameters defining these numbers are dependent on the temperature. The changes in these parameters with the change in temperature will be difficult to be accounted for, especially during a computer simulation, unless temperature dependent models representing these parameters are determined. There are two models developed to calculate $\boldsymbol{h_w}$. One model is based on McAdam's correlations and the other one is based on Churchill and Bernstein's correlation. The dependency of these parameters on temperature is obtained by using the linear polynomial curve fitting method. The models are then used as part of a MATLAB program to evaluate $\boldsymbol{h_w}$ due to wind blowing across the cylindrical receiver of a parabolic trough concentrator.

Introduction

Fluid flowing across cylinders and spheres normally involves flow separation, which has been proven to be difficult to be analysed analytically. The flow can be laminar or turbulent, entirely depending on the flow conditions. It is therefore useful to know the nature of the flow, especially in evaluating the Nusselt number, which is used in the computation of the wind heat transfer coefficient, $\boldsymbol{h_w}$. The computational analysis of $\boldsymbol{h_w}$ over any kind of geometrical shapes is rather tedious, especially if it is carried out in an environment where the temperature changes significantly. The properties of the parameters involved in evaluating $\boldsymbol{h_w}$ can be obtained from data handbooks but only to a certain limit. This is due to the fact that the supplied data is recorded at certain temperature intervals. The resolution of the data depends on these temperature intervals. This limitation can slow down a computer simulation process, whereby a large database system must be created, just to cater for the change in values for certain temperature dependent parameters. There were problems encountered especially when having to deal with the temperature dependant parameters, such as density ρ, kinematic viscosity ν, dynamic viscosity μ, specific heat capacity $\boldsymbol{C_p}$ and thermal conductivity $\boldsymbol{k}$ of the fluid flowing during a computer simulation process. If the fluid gains heat, there will be an increase in temperature and this causes variation in the values of the temperature dependant parameters. Although the best way of solving the problems encountered will be to do experimental studies, but due to the popularity of certain shapes, such as spheres and cylinders, several empirical correlations have been developed and can be used to evaluate h_w. In this study, the correlations used are based on McAdams equations and also on Churchill and Bernstein's comprehensive correlation for fluid flowing over a cylinder.

Theory

Reynolds, Nusselt and Prandlt numbers are normally used to evaluate the wind heat transfer coefficient, h_w of a cylindrical receiver of a parabolic trough concentrator. The properties of parameters defining these numbers are dependent on temperature. The general relationship between h_w and Nusselt number is given in Eq. (1), while the Reynolds number can be evaluated with Eq. (2), depending on the mean flow velocity V, cover diameter D_{co} and the kinematic viscosity ν.

$$h_w = \frac{Nu\,k}{D_{co}} \tag{1}$$

$$\mathrm{Re} = \frac{VD_{co}}{\nu} \tag{2}$$

Prandlt number, named after Ludwig Prandtl is given in Eq. (3), where μ is the dynamic viscosity, C_p and k is the specific heat capacity and thermal conductivity of the fluid flowing in the tube respectively.

$$\mathrm{Pr} = \frac{\mu C_p}{k} \tag{3}$$

The evaluation of h_w was done based on McAdams[1] equations and also by using the comprehensive correlations proposed by Churchill and Bernstein[2], for wind blowing over a cylinder. McAdams correlations, increased by 25% for outdoor situations, are given as Eq. (4) and (5).

$$Nu = \left[0.32 + 0.43\,(Re)^{0.52}\right](1.25) \qquad 0.1 < \mathrm{Re} < 1000 \tag{4}$$

$$Nu = 0.24\,(Re)^{0.6}\,(1.25) \qquad 1000 < \mathrm{Re} < 50000 \tag{5}$$

Churchill and Bernstein's correlation is given as Eq. (6) which includes the Prandlt number as well.

$$\mathrm{Nu} = 0.3 + \frac{0.62\,Re^{1/2}\,Pr^{1/3}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}}\left[1 + \left(\frac{Re}{28200}\right)^{5/8}\right]^{4/5} \tag{6}$$

Methodology

In order to use the McAdams equations, the following equations were derived and two new factors were introduced. By considering these two factors, it becomes obvious that the evaluation of wind coefficient will definitely differ at different temperatures, as most of its parameters are temperature dependent. The first step towards obtaining a temperature dependent model, in order to simplify and introduce flexibility in evaluation is by refining the given equations. If we simplify Eq. (4) and Eq. (5), the following equations are obtained;

$$\mathrm{Nu} = 0.4 + 0.54\,(Re)^{0.52} \qquad 0.1 < \mathrm{Re} < 1000 \qquad (7)$$

$$\mathrm{Nu} = 0.3\,(Re)^{0.6} \qquad 1000 < \mathrm{Re} < 50000 \qquad (8)$$

Since Eq. (7) and Eq. (8) are both dependent on the Reynolds number, the next step is to manipulate Eq. (2) as follows;

$$\mathrm{Re} = VD_{co}\left(\frac{\rho}{\mu}\right) = VD_{co}(R_{AIR}) \qquad (9)$$

where R_{AIR} is the ratio of the fluid's density to its dynamic viscosity.

By using Eq. (1), $\boldsymbol{h_w}$ can be obtained entirely dependent on the value of the Reynolds number. The following Eq. (10) and Eq.(11) are then used for simulation purposes and the respective factors as expressed in the equations below are obtained through curve fitting methods. By introducing these factors, the nuisance of creating a database to handle the large volume of data for the properties of the fluid is omitted. It would now be easier and quicker to evaluate $\boldsymbol{h_w}$ even for continuously changing temperatures.

$$h_w = \left[\frac{(0.4 + 0.54\,(Re)^{0.52})}{D_{co}}\right] K_{FACTOR} \qquad 0.1 < \mathrm{Re} < 1000 \qquad (10)$$

$$h_w = \left[\frac{(0.3\,(Re)^{0.6})}{D_{co}}\right] K_{FACTOR} \qquad 1000 < \mathrm{Re} < 50000 \qquad (11)$$

These two equations will be referred to as Model 1, as only one equation will be used at any one time to evaluate $\boldsymbol{h_w}$ based on the calculated Reynolds number.

Model 2 on the other is based on the Churchill and Bernstein's correlation as expressed in Eq. (6). For both of the models, Eq. (3) is represented by using the P_{FACTOR} which is computer evaluated as follows;

$$\mathrm{Pr} = P_{FACTOR} \qquad (12)$$

The method used to find the relationship between the parameters defining the K_{FACTOR}, P_{FACTOR} and R_{AIR} and their dependencies on temperature is by using curve-fitting procedures. Before the curve fitting procedures are applied, the values of K_{FACTOR}, P_{FACTOR} and R_{AIR} are calculated individually at different temperatures.

Results

The curve fitting method that gave the best correlation for K_{FACTOR}, P_{FACTOR} and R_{AIR} with the lowest standard errors is the polynomial curve fit method[3] and the general form is given as Eq. (13) below;

$$Y = a + bT + cT^2 + dT^3 + eT^4 + fT^5 + gT^6 + hT^7 + iT^8 \qquad (13)$$

The following Table 1 shows the coefficients that fit into Eq. (8) and used to evaluate the respective K_{FACTOR}, P_{FACTOR} and R_{AIR} at the required temperatures.

	Polynomial Fit Coefficients Data		
Y / Coefficients	P_{FACTOR}	K_{FACTOR}	R_{AIR}
a	7.1506881E-01	2.42117780E-02	7.5116824E+04
b	-4.0626767E-04	6.99101920E-05	-4.8362226E+02
c	3.8161734E-06	1.79584550E-07	3.3643226E+00
d	-2.5249700E-08	-1.81336580E-09	-4.3288691E-02
e	7.9610385E-11	6.38637920E-12	4.8705166E-04
f	-9.0197855E-14	-7.87637930E-15	-3.2277568E-06
g	0	0	1.1962313E-08
h	0	0	-2.3159830E-11
I	0	0	1.8287771E-14

Table: *Polynomial fit coefficient values to be used in Eq. (13) to obtain the temperature dependent equations for* K_{FACTOR}, P_{FACTOR} *and* R_{AIR}.

After all the parameters used to build the two models are obtained, a simple program is written in MATLAB to demonstrate the application of these models.

The program listing is given in Table 2 and the results are shown in the Fig. 1 below.

```
% Simple program to calculate the wind heat transfer coefficient
% over the cylindrical receiver of a Parabolic Trough Concentrator
% Input data
T=30;
V=3;
Dco=0.01:0.01:0.5;
% Evaluation of KFactor for air
Ka=2.42117780E-02;
Kb=6.99101920E-05;
Kc=1.79584550E-07;
Kd=-1.81336580E-09;
Ke=6.38637920E-12;
Kf=-7.87637930E-15;
Kg=0;
Kh=0;
Ki=0;
KFactor=Ka+(Kb*T)+(Kc*(T^2)+...
   (Kd*(T^3))+(Ke*(T^4))+(Kf*(T^5))...
   +(Kg*(T.^6))+(Kh*(T.^7))+(Ki*(T.^8)));
% Evaluation of Pfactor
Pa=7.1506881E-01;Pb=-4.0626767E-04;
Pc=3.8161734E-06;Pd=-2.5249700E-08;
Pe=7.9610385E-11;Pf=-9.0197855E-14;
Pg=0,Ph=0,Pt=0
Pfactor=Pa+(Pb*T)+(Pc*(T.^2))+(Pd*(T.^3))+...
      (Pe*(T.^4))+(Pf*(T.^5))+(Pg*(T.^6))+...
      (Ph*(T.^7))+(Pt*(T.^8));
% Evaluation of Rair
Ra=7.5116824E+04;Rb=-4.8362226E+02;
Rc=3.3643226E+00;Rd=-4.3288691E-02;
Re=4.8705166E-04;Rf=-3.2277568E-06;
Rg=1.1962313E-08;Rh=-2.3159830E-11;
Ri=1.8287771E-14;
Rair=Ra+(Rb*T)+(Rc*(T.^2))+(Rd*(T.^3))+...
      (Re*(T.^4))+(Rf*(T.^5))+(Rg*(T.^6))+...
      (Rh*(T.^7))+(Ri*(T.^8));
RE=(V*Dco*Rair)
% McAdams(1954) Correlations for outdoor conditions
% Model 1
if RE<1000
   Model1=((0.4+(0.54.*(RE.^0.52)))./Dco).*(KFactor)
elseif RE>1000
        Model1=((0.3.*(RE.^0.6))./Dco).*(KFactor)
end
% Churchill and Bernstein's Correlation
% Model 2
Nu1=((RE./28200).^(5/8));
Nu2=(1+Nu1).^(4/5);
Nu3=0.62.*(RE.^0.5).*(Pfactor.^(1/3));
Nu4=(1+((0.4./Pfactor).^(2/3))).^(1/4);
Nu5=Nu3./Nu4;
Nu6=Nu5.*Nu2;
Nu=0.3+Nu6;
Model2=(Nu.*KFactor)./Dco;
%Output Data
q=Model1',Model2'
```

***Table 2:** A simple program to be used in the MATLAB environment.*

The results shown in Fig. 1 is obtained after running the above program and the correlation factor between the results of the two models is around 90%. One may choose any of the models to be used in their simulation work of perhaps the entire system, especially in evaluating the overall heat loss coefficient.

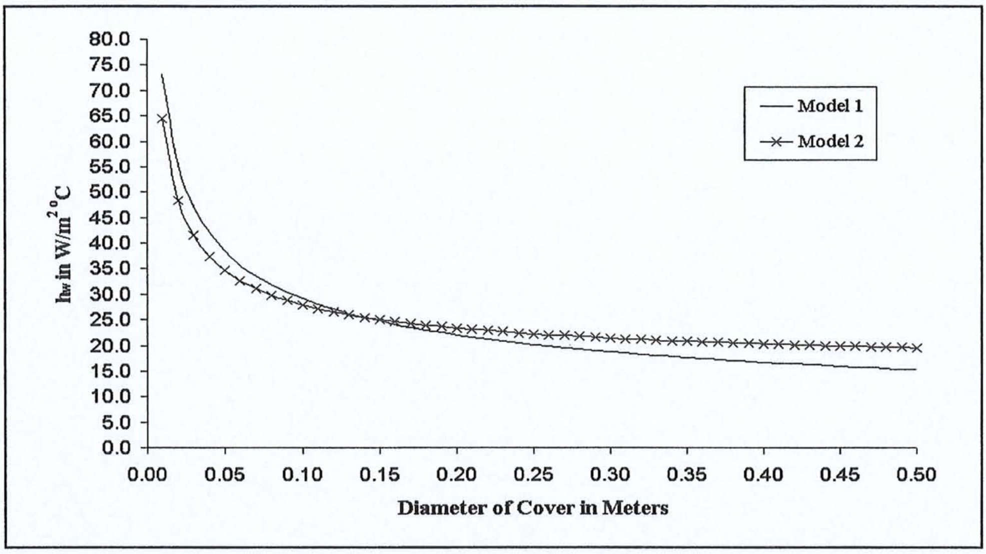

Fig. 1: *Graph showing the variation in computed h_w at 30°C with the varying of the diameter cover and evaluated using the two models.*

Conclusion

By using this methodology to evaluate the heat transfer coefficient due to wind blowing across a cylindrical receiver of a parabolic trough concentrator, the independence from evaluating the fluid properties at certain constant or continuously changing temperature is achieved at acceptable error. The need to include bulk database of physical properties has certainly become a thing of the past and close matching values for a given temperature can be computed by extrapolating or interpolating, depending on the correlation factors.

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