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Numerical Investigation of Hot Oil Velocity Effect on Force Heat Convection and Impact of Wind Velocity on Convection Heat Transfer in Receiver Tube of Parabolic Trough Collector System

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Abstract**—**A solar receiver is designed for operation under extremely uneven heat flux distribution, cyclic weather, and cloud transient cycle conditions, which can include large thermal stress and even receiver failure. In this study, the effect of different oil velocity on convection coefficient factor and impact of wind velocity on local Nusselt number by Finite Volume Method will be analyzed. This study is organized to give an overview of the numerical modeling using a MATLAB software, as an accurate, time efficient and economical way of analyzing the heat transfer trends over stationary receiver tube for different Reynolds number. The results reveal when oil velocity is below 0.33m/s, the value of convection coefficient is negligible at low temperature. The numerical graphs indicate that when oil velocity increases up to 1.2 m/s, heat convection coefficient increases significantly. In fact, a reduction in oil velocity causes a reduction in heat conduction through the glass envelope. In addition, the different local Nusselt number is reduced when the wind blows toward the concave side of the collector and it has a significant effect on heat losses reduction through the glass envelope.

Keywords**—**Receiver tube, heat convection, heat conduction, Nusselt number.

I. Introduction

SOLAR energy is known as the most efficient, clean and affordable energy alternatives available today [1]. After the solar energy is becoming globalization and can find the special seat among industrial and scientific sectors, the majority of firms and companies had some idea about how to increase and improve that type of technology. In order to keep continual supply of solar energy, thermal energy storage system has been introduced as a solar thermal energy harvesting system. Thermal storage will also be beneficial if consumers can release surplus power during peak demand hours [2].

Concentrating solar power technologies are the promising for process heating and power generation applications in recent year. Parabolic Trough Collector (PTC) is the most matured technology for large scale exploration of solar energy with high dispatch ability. Solar receivers with optical concentration technology need to operate under extremely uneven heat flux [3], [4], cyclic weather and cloud transient cycle conditions, which can result in high temperature gradients [5], [6].

Thermal efficiency of receiver system depends on the rate of heat transfer by different tube layers. M. J. Montes et al. [7] indicated that conduction heat transfer can reduce through the absorber tube if tube diameter and thickness parameter are decreased. H. Price [8] revealed that natural heat convection can be ignored between glass envelope and absorber tube if vacuum is maintained through the space. Results of [9] performed that the convective coefficient value through the glass envelope in windy case is two times higher than one for non-windy case.

The present study aims to investigate the effect of various oil velocities on convection coefficient through the absorber tube and impact of wind velocity on local Nusselt (Nu) on glass envelope in receiver system.

II. Governing Equations

According to [10], convective heat transfer, conductive heat transfer and heat radiation take place through the receiver system. Figs. 1, 2 show heat transfer resistance in different receiver parts.

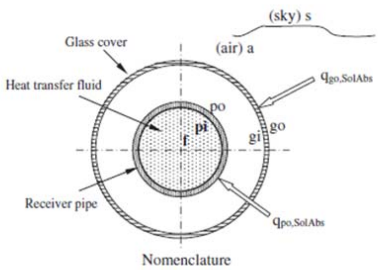

Fig. 1 Collector receiver model of nomenclature

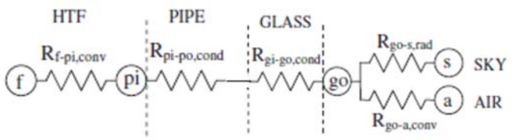

Fig. 2 Thermal resistance model for the cross-section of the receiver

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A. Convection Heat Transfer between Hot Fluid and Absorber Tube

Based on Newton's law heat convection between hot oil through the absorber tube and inner diameter of absorber wall is presented by [11];

$$q_{f-pi,conv}=h_f \pi D_{pi}(T_{pi}-T_f) \tag{1}$$

$$h_f=Nu_{D_{pi}}\frac{k_f}{D_{pi}} \tag{2}$$

According to heat transfer theory Nu number is estimated by type fluid flow and Re. As turbulent flow is considered, Nu number can be determined by;

$$Nu_{Dpi}=\frac{\frac{f_{pi}}{8}*(Re_{D_{pi}}-1000)*Pr_f}{1+12.7\sqrt{\frac{f_{pi}}{8}}(Pr_f^{\frac{2}{3}}-1)} \tag{3}$$

For $0.5<Pr_f<2000$ and $2300<Re_{D,pi}<5*10^6$

$$f_{pi}=[1.82\log(Re_{D,pi})-1.64]^{-2} \tag{4}$$

B. Conduction Heat Transfer through the Absorber Wall and Glass Envelope

Heat conduction equations for absorber tube and glass envelope are formulated by (5) and (6) respectively;

$$q_{pi-po,cond}=\frac{2\pi k_{pipe}(T_{pi}-T_{po})}{Ln(\frac{D_{po}}{D_{pi}})} \tag{5}$$

$$q_{gi-go,cond}=\frac{2\pi k_{Glass}(T_{gi}-T_{go})}{Ln(\frac{D_{go}}{D_{gi}})} \tag{6}$$

C. Convection Heat Transfer between Atmosphere and Glass Envelope

Natural heat convection takes place if there is no wind case around the receiver tube. The correlation developed by Churchill and Chu is used to estimate the Nu [12];

$$Nu_{D,go}=[0.6+\frac{0.387Ra_{D,go-a}^{\frac{1}{6}}}{\{1+\left(\frac{0.559}{Pr_{go-a}}\right)^{\frac{9}{16}}\}^{\frac{8}{27}}}]^2 \tag{7}$$

$$Ra_{D,go}=\frac{g\beta(T_{go}-T_a)D_{go}^3}{v_{go-a}^2}Pr_{go-a} \tag{8}$$

$$\beta=\frac{1}{T_{go-a}} \tag{9}$$

$$Pr_{go-a}=\frac{v_{go-a}}{\propto_{go-a}} \tag{10}$$

Sometimes the wind velocity is not negligible. Therefore, force convection heat transfer is considered between environment and glass envelope. Nu can be calculated by the [11];

$$Nu_{D,go}=CRe_{D,go}^m Pr_a^n \tag{11}$$

$$0.7<Pr_a<500$$

$$1<Re_{d,go}<10^6$$

D. Radiation between Environment and Glass Envelope

Radiation heat transfer occurs by assuming that the glass cover is a small convex gray object in a large blackbody cavity the sky [11].

$$q_{go-s,rad}=\sigma\varepsilon_{go}\pi D_{go}(T_{go}^4-T_s^4) \tag{12}$$

III. Survey Data

Shiraz is one of the cities where parabolic trough power plant system has been installed. Specification of receiver system and physical property of glass envelope have been collected by Tables I and II [13];

TABLE I
SPECIFICATION OF RECEIVER SYSTEM

Symbol	Receiver parameter	Value
D_{go}	Outer diameter of glass envelope	12.5 cm
D_{gi}	Inner diameter of glass envelope	11cm
D_{po}	Outer diameter of absorber	7cm
D_{pi}	Inner diameter of absorber	6.56 cm

TABLE II
PHYSICAL PROPERTIES OF GLASS ENVELOPE

Density (kg/m^3)	Young's modulus (MPa)	Thermal conductivity (W/m^{2}K)
2500	73.1	1.4

According to [14], absorber tube of receiver system has been made by AISI 316L Stainless Steel. Table III has provided density, thermal conductivity and young's modulus of this material.

TABLE III
PHYSICAL PROPERTIES OF ABSORBER TUBE

Density (kg/m^3)	Young's modulus (MPa)	Thermal conductivity (W/m^{2}K)
8000	193	16.3

The oil used for receiver system in Shiraz solar power plant is considered VP1 oil. Some physical properties of VP1 oil are given by;

$$\rho=-0.90797T+0.0078116T^2-2.367E-6T^3+1083.25 \tag{13}$$

$$c_p=0.002414T+5.9591E-6T^2-2.9879E-8T^3+4.4172E-11T^4+1.498 \tag{14}$$

$$k=-8.19477E-6T-1.92257E-7T^2+2.5034E-11T^3-7.2974E-15T^4+0.137743 \tag{15}$$

$$v=e^{(\frac{544.149}{T+114.43}-2.59578)} \tag{16}$$

Based on [13], the outdoor conditions for four seasons have been provided by Table IV;

TABLE IV
THE OUTDOOR CONDITIONS OF SOLAR POWER PLANT SITE

Solar parameters	Fall	Winter	Spring	Summer
Ambient temperature	30°C	12°C	17.5°C	33.5°C
Wind velocity	2m/s	1.5m/s	2.8m/s	2m/s
Sky temperature	5.07°C	-13.28°C	0°C	9.17°C
Monthly irradiance	943W/m2	998W/m2	1032W/m2	955W/m2

IV. Result and Discussion

Based on physical properties of VPI oil and absorber tube and also governing equations, numerical results are obtained in the outer and inner layer of receiver tube.

In this section, heat transfer parameters at the first step between hot oil and absorber tube during a day with three different oil velocities through longitudinal absorber tube are discussed and then heat transfer result between glass envelope and environment in windy case and non-windy case are analyzed.

A. Convection Heat Transfer between Hot Fluid and Absorber Tube

In order to find the physical properties of VP1 oil, some initial data like inlet temperature will be needed. According to (REF), range of inlet temperature is considered between 20°C and 200°C through the receiver system.

Based on heat transfer theory for turbulent flow, the Re is described between 10^5 to 2E6 in different range of oil velocity. Therefore, friction factor pipe and Nu can be obtained by (4) and (3) respectively.

Convection heat transfer between hot oil and glass envelope depends on inlet and outlet temperature, physical properties of oil used and the most important factor is mass flow rate of oil. Since, temperature alert factor can cause the mass flow rate value and this factor leads to change oil velocity, Convection heat transfer can take place by three types of oil velocities [15]. Low mas flow rate occurs in the low temperature and in the summer time, oil velocity raises up dramatically. The relationship between oil temperature and Re, temperature against friction factor, oil temperature versus Nu and finally Re versus Nu are shown by Figs. 3-5.

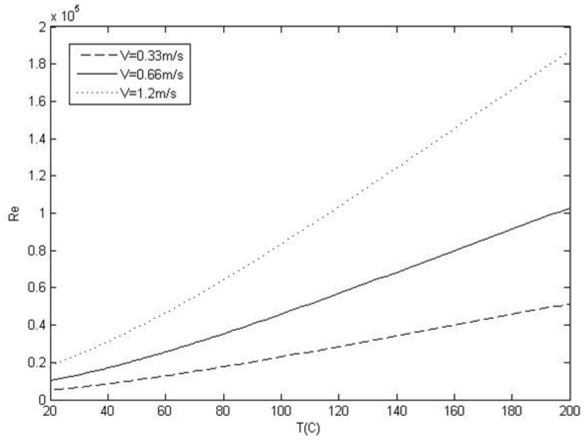

Fig. 3 Reynolds vs oil temperature graph for various types of oil velocities

As can be seen, the relationship between Nu and oil temperature is not directly proportionate. At the low temperature, slope of Nu trends became horizontally because physical properties of oil such as Pr is not changing significantly.

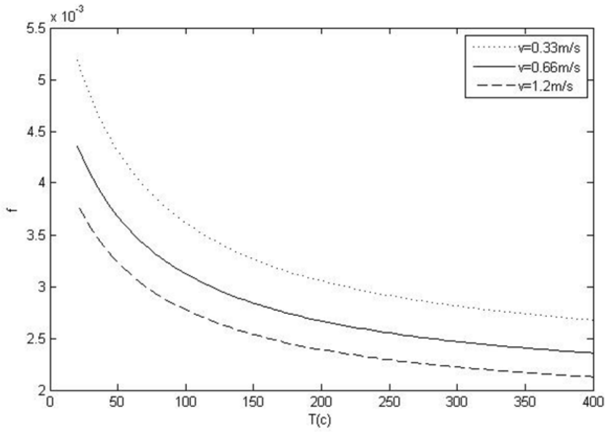

Fig. 4 Friction factor vs oil temperature graph for various types of oil velocities

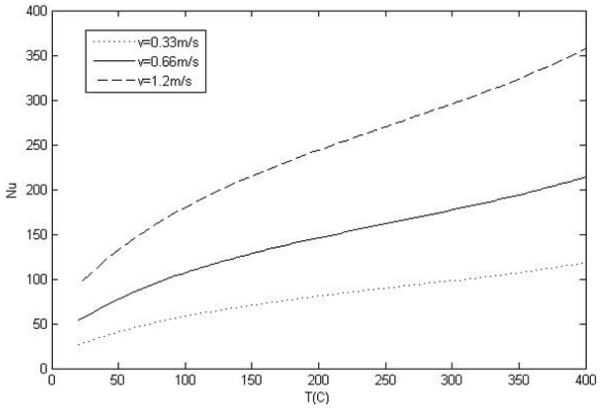

Fig. 5 Nu vs oil temperature graph for various types of oil velocities

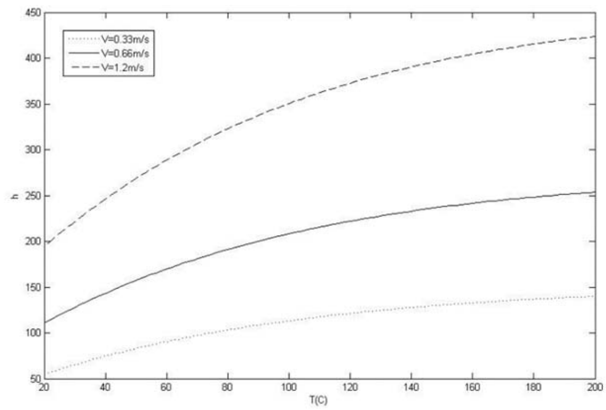

Fig. 6 Convection coefficient vs oil temperature graph for various types of oil velocities

Coefficient of convection against oil temperature is shown by Fig. 6. As can be seen, the highest value is associated with the highest oil velocity (1.2 m/s). According to Fig. 6, the coefficient of convection is 423W/m^2°C, 253 W/m^2°C and 140 W/m^2°C at 200°C when oil velocity is considered around 1.2m/s, 0.66m/s and 0.33m/s respectively. Therefore, the relationship between oil velocity and convection coefficient is directly proportionate.

As can be seen by Fig. 6, total heat convection value is increased significantly when oil velocity is over 1m/s. it can be noted that, an increase in heat convection through the absorber tube causes an increase in heat conduction through the glass envelope and absorber wall. Since, this receiver system utilizes at power system and inlet temperature is more than 50°C, the value of heat convection is considered and totally, that value can have inverse effect on total receiver efficiency. In order to reduce total heat losses, mass flow rate must decrease and consequently temperature gradient reduces. In fact, mass flow rate of oil decreases when oil velocity is decreased and hence total heat conduction will be reduced.

B. Convection Heat Transfer between Atmosphere and Glass Envelope

Convection heat transfer through the glass envelope takes place in two different cases. In windy case, force heat convection occurs and in the calm case, natural heat convection is considered.

1) Windy Case

There is force heat convection when wind velocity is not ignored around the receiver system. According to S. [15] four different ambient temperature would be considered. Based on [16], the wind velocity in solar power plant site is estimated between 1m/s to 15m/s. the glass temperature value is assumed 350K [17].

In order to find Nu in windy case, The constant n,m and C must be calculated. Based on heat transfer theory, constant n is around 0.36 for Pr<10. In addition, the rest constants have been provided by Table V [10].

TABLE V
CONSTANTS VALUE

Re	C	m
1-40	0.75	0.4
40-1000	0.51	0.5
1000-200000	0.26	0.6
200000-1000000	0.076	0.7

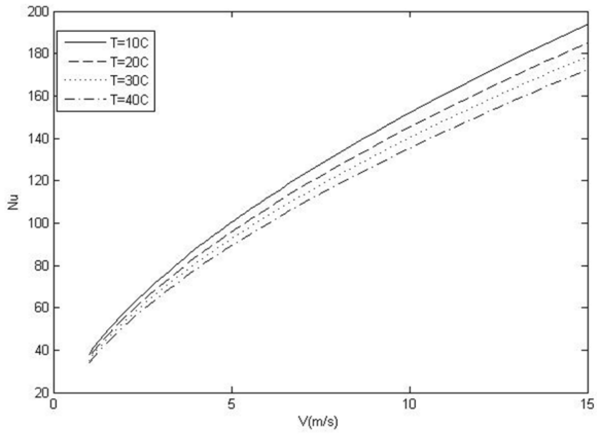

Fig. 7 Nu vs wind velocity graph at four different ambient temperatures

As the range of Re is between 10^4 and 8E4, the third row of Table V should be considered. The value of Nu against wind velocity in Shiraz site is shown by Fig. 7.

In winter time, Nu is the highest value. Based on Fig. 7, Nu=193 when wind velocity is 15m/s. it is more than five times much as wind velocity at 1m/s. Based on (11), the highest convection coefficient occurs when maximum wind velocity is reported. Figs. 8 and 9 illustrate convection coefficient against wind velocity at T=10°C and T=40°C.

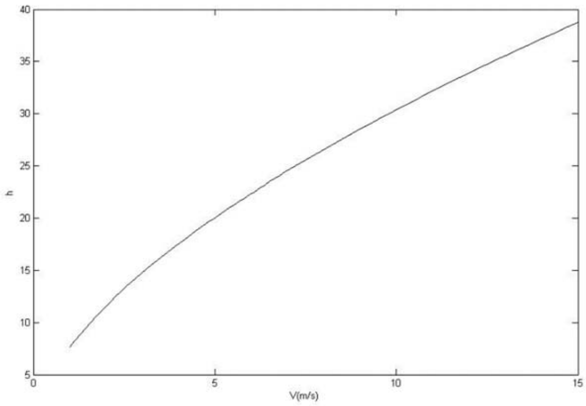

Fig. 8 Convection coefficient vs wind velocity graph at T=10C

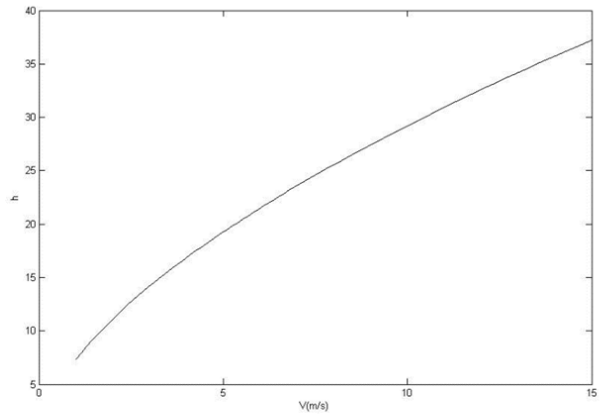

Fig. 9 Convection coefficient vs wind velocity graph at T=40C

In windy case where wind velocity is over 8m/s, Nusselt number is estimated around 100 (based on Fig. 8), so convection coefficient of heat transfer is approximately 30 W/m2°C (based on Figs. 8 and 9). Therefore, forced heat convection and heat radiation should be calculated simultaneously. Moreover, it has an effect on heat conduction through the glass envelope [19]. Since, the difference temperature between glass envelope and environment is considered in the cold times, the value of forced heat convection is high and totally that value can have inverse effect on total heat losses. In order to improve total receiver efficiency, conduction heat transfer through the glass envelope can be considered. According to (6), temperature gradient which is function of heat conduction should be decreased. There are several ways for reducing temperature gradient.

Based on research by numerical and simulation methods by [18], when receiver system filled by half insulated annulus, convection heat transfer was found to be reduced by 25%. In contrast, there was significant increase in convection heat transfer when it was filled by air-filled annulus. Since, this system contains track components; the difference of local Nu reduces when the wind blows toward the concave side of the collector. Moreover, Average Nu is less affected by increasing wind speed when the receiver tube is on the backward side [17].

2) Non-Windy Case

Table VI compares Nu between windy case and non-windy case. As can be seen, the highest Nu can be obtained at the highest wind velocity, whereas Nu is very low at non-windy case. In can be noted that, when speed of wind is lower than 5m/s, natural heat convection is considered on glass envelope surface.

TABLE VI
COMPARISON BETWEEN NON-WINDY AND WINDY CASE AT FOUR DIFFERENT AMBIENT TEMPERATURES

Case	Temperature	Velocity	Nu
Non-windy	30 °C	0	13.5
Windy case	40°C	1m/s	33.97
		5m/s	88.79
		10m/s	135.06
		15m/s	172/5
	20°C	1m/s	36.46
		5m/s	95.3
		10m/s	145.06
		15m/s	185.1
	10°C	1m/s	38.17
		5m/s	99.76
		10m/s	152.4
		15m/s	193.8
	30°C	1m/s	35.23
		5m/s	92.08
		10m/s	140.7
		15m/s	178.9

It can be found that low Nu in non-windy or low windy case can be an advantage to enhance of thermal efficiency of receiver. It can reduce heat conduction through the glass envelope and overall heat losses should be decreased considerably.

V. CONCLUSION

In this research, convection heat transfer through the absorber tube, natural and force heat convection in calm and windy cases were analyzed. Based on all available data in this research, the following conclusions are drawn;

- Obtaining results through the absorber tube part show that the heat convection value is negligible at low oil velocity and low temperature. Convection coefficient was dropped dramatically to 140W/m^2°C at the same temperature when oil velocity raised up to 0.33m/s. In fact, an increase in oil velocity led to increase in coefficient of heat convection and hence an increase in heat conduction in absorber tube. The best strategy to reduce heat conduction, is to control and decrease of mass flow rate of oil.
- The highest force heat convection coefficient through glass envelop took place when wind velocity was reported in the wintertime. The value of convection coefficient was 30W/m^2°C when wind velocity was 15m/s. Since, this system contains track components; the difference of local Nu reduces when the wind blows toward the concave side of the collector. In addition, average Nu is less affected by increasing wind speed when the receiver tube is on the backward side.
- Based on Table VI, the local Nu in non-windy case and low windy are negligible. In fact, when the speed of wind is lower than 5m/s, natural heat convection takes place on glass envelope surface. It can be found that low Nu in non-windy or low windy case can be an advantage to enhance of thermal efficiency of receiver. It can reduce heat conduction through the glass envelope and overall heat losses should be decreased considerably.
- At the end, in order to determine total efficiency, heat convection through glass envelope and absorber wall play an important role. In view of Finite Element Analysis application in heat transfer, oil temperature is considered as the inlet temperature and based on matrix approach, it can have significant effect on the outer region of receiver. In fact, it has a significant effect on heat conduction through the absorber wall.

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