Analysis of Heat Losses of Absorber Tubes of Parabolic through Collector of Shiraz (Iran) Solar Power Plant

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Abstract—In this article heat losses of absorber tubes of parabolic trough collectors for the collector field of 250 kW Shiraz (Iran) solar thermal power plant is evaluated for various conditions. For analysis, both experimental measurements and numerical modeling are made to find the impact of failure of heat collecting tubes. The amount of heat losses are compared numerically for 3 different types of tubes; vacuum, lost vacuum (air) and broken glass (bare) tube. The experimental measured data are used to validate the numerical simulation. For temperature measurements around the glass tube and absorber tube an infrared thermograph (IR) camera is used. Thermal images are calibrated with measuring some local temperatures. For theoretical simulation a commercial code for thermal analysis of parabolic collectors are used. An absorber tube with vacuum reduces significantly the heat losses in comparison with broken tube or tube without vacuum. During power plant operation poor isolation or any glass tube failure should be avoided for any solar thermal power plants.

Index Terms—Heat loss, Parabolic trough collector, Thermal efficiency, Infrared (IR) camera.

I. INTRODUCTION

The current industrial growth and environmental impacts show that solar energy for solar thermal power plants is the most promising of the unconventional energy sources. The most common commercially available solar power plants use parabolic trough concentrators.

A parabolic collector includes the receiver tube, the concentrator, power transmition, collector structure. The receiver is the element of the system where solar radiation is absorbed and converted to thermal energy. It includes an absorber tube, its associated glass cover, and insulations at its end.

For the first 250 kW pilot solar thermal power plant in Shiraz, Iran, the collector circuit consists a field of 48 solar parabolic trough collectors such as shown in Fig. 1, arranged in modules operating in tracking mode and containing oil as their working fluid [1]. The working fluid in the receiver tube absorbs solar energy and transfers it to water in heat exchangers to produce hot water or steam. The receiver is covered by a glass tube to reduce thermal radiation as well as convection heat loss to the free air which moves around the receiver. To reduce further the heat losses from the absorber, air is evacuated from the space between absorber and glass cover [2]. Several researches have been performed to study different absorber tubes performance, such as porous finned absorber tubes [3]

and tubes with inserted twisted tapes[4]. The absorber tube of the present collector has 7 cm outer diameter and glass cover has 12 cm outer diameter. For the design condition described in Ref.[2], the working fluid approaches to 265^0C. Heat loss from glass cover to ambient air is by thermal radiation and mostly by convection. The surrounding air is usually turbulent and crosses the glass tube and exchange heat between glass outer surface and ambient air. Convection heat loss from the glass cover depends on the ambient wind flow, air temperature and glass cover temperature. The air may have low speed and hence free convection is dominant or it may have some momentum, in which case combined free and forced convection occurs. If the wind blows with some speed forced convection takes place. For most cases, such as the region of 250kW Shiraz power plant the wind blows most of the time througho ut the year[1]. During the lifetime of a parabolic trough collectors power plant, some absorber segments lose vacuum and there after suffer from significant convective heat loss. In this study an IR-Thermography method is used to evaluate the heat loss of parabolic trough collectors tube by measuring the glass surface temperature of tubes. The results are compared with a numerical 3D model of a 4m parabolic trough collectors for 3 different types of tube: 1-vaccum jacket tube, 2-lost vacuum tube, 3- broken glass tube. This paper describes a combined conduction, convection, and radiation heat transfer model for the receiver tube. it includes the effects of nonuniform solar flux on the absorber tube, surface temperature of absorber tubes for 3 different types of tube which is mentioned earlier. For such positions which are not possible to measure experimentally with a thermograph camera, numerical simulation is used to find temperature field of the absorber surface. Different components of an absorber tube are illustrated in Fig. 2.

Fig. 1. Parabolic collector with absorber tube of Shiraz solar power plant [1]

II. GOVERNING EQUATIONS

Heat transfer from the absorber tubes include,

qconv_g_sky and qrad_g_sky, the convective and radiative heat transfer loss from the outer surface of glass tube to the environment [6].

$$q_{thermalloss} = q_{conv-g-sky} + q_{rad-g-sky} \qquad (1)$$

$$q_{conv-g-a} = h_c (T_g - T_a).A_{glass} \qquad (2)$$

where T_g and T_a are glass temperature and ambient temperature , A_{glass} is glass envelope area and hc is the convective heat transfer coefficient of air,which is calculated from Mullick & Nanda correlation[7]:

$$hc = 4d^{-0.42} v^{0.5} \qquad (3)$$

where V_w is the wind velocity in m/s and D is the outer diameter of glass cover in m.

$$q_{rad\_g\_a} = \sigma.\varepsilon_g.(T_g^4 - T_{sky}^4).A_{glass} \qquad (4)$$

where σ is Stephan Boltzman coefficient, ε_g is glass envelope emissivity and T_{sky} is sky temperature. For turbulent oil flow inside the absorber, governing equations are continuity, momentum, Energy, RTE equations and k-ε for turbulent modeling [6].
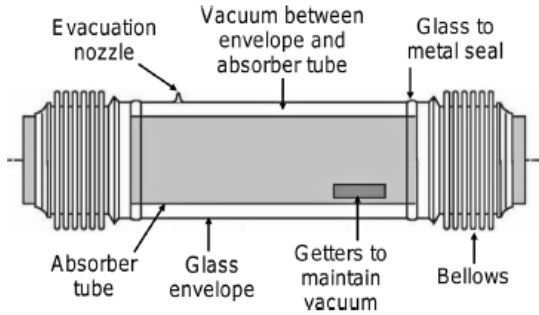

Fig. 2. Components of an absorber tube of parabolic trough colectors [5]

III. HEAT LOSSES

Experimental (Thermography) and numerical method are used to calculate heat loss for 3 different types of tube which are shown in Fig. 3- Fig. 5;
1) vacuum jacket tube
2) lost vacuum tube
3) broken glass tube

Shiraz parabolic trough collectors specification are tabulated in Table I.

TABLE I: COLLECTORS SPECIFICATIONS [8]

Absorber tube length	4.06 m	Absorptivity of absorber tube	0.94
Outer diameter of absorber tube	7 cm	Geometric concentration ratio (G_c)	14
Inner diameter of absorber tube	6.56 cm	Aperture of collector	3.1 m
Outer diameter of glass tube	12.5 cm	Width	3.4 m
Inner diameter of glass tube	11 cm	Focal length	88 cm
Emissivity of absorber tube	0.15		

The absorber is made by SCHOTT Factory in Germany. The absorber tube is made by AISI 316L [8]. The working fluid used in the absorber tube is Behran-oil with properties mentioned in Ref.[8].

A. IR-Thermography Method (Experimental)

A Testo 881 IR-Thermograph camera is used for glass envelope surface temperature measurements. Because the receiver glass envelope is essentially opaque to infrared (IR) radiation, all the thermal losses from the receiver must pass, via conduction, through the glass envelope. As a result, the radiant and convective thermal losses from the receiver are directly related to the glass envelope temperature and it does not matter what is happening inside the glass tube(for example, the type and quality of the selective coating, whether the vacuum is good or bad, or the HTF fluid temperature). The thermal losses can be correlated directly with the glass envelope temperature for known air temperature and wind speed. The procedure required collectors to be defocused while measurements were taken on each receiver with a hand-held IR temperature measurement gun. The collector had to be defocused so that the crews were able to get close enough to take the measurements. The IR gun reads the temperature of a relatively small spot. Several readings were taken on each receiver to obtain a more representative average glass temperature. The IR camera measures the emitted IR radiation from an object. Because the emitted radiation is a function of the surface temperature of the object, the temperature of the surface can be determined if the emittance of the surface is known, for this many cross sections has been selected on each receivers. For each cross-section, the average temperature is determined. This temperature is assumed to be the glass temperature of the receiver at this cross section. The average value for each of the cross- sections is used to calculate average glass temperatures for each receiver.

Fig. 3-5 shows IR images taken of 3 different types of parabolic trough receiver. From the images, the receiver, receiver supports, mirrors, and sky are clearly identifiable. The color of the image represents the intensity of the IR signal and temperature. The results of thermography method are tabulated in Table II.

B. Numerical Method

In this study, by using common CFD software, the three mentioned absorber tubes are modeled for linear collectors of Shiraz solar power plant condition. Navier Stokes and energy equations are solved to analyze the fluid inside the tubes. Discrete ordinate model is used for analyzing radiation in the vacuum space between the absorber tube and the transparent glass tube and ultimately the k-ε model is considered for turbulence modeling. The model is validated, based on published reports of experimental data [9].

1) Boundary Condition

In our solution, a 4m absorber tube is considered. Boundary condition is clarified in Fig. 6. It must be mentioned that the non-uniform distribution of radiation heat flux (Fig. 6), is considered, around the absorber tube which is a function of local concentration ratio (Fig. 7) and the rim angle of PTC's. The wind velocity is considered 1.5 m/s and the inlet temperature of oil is assumed 200 °C.

2) *Grid Study*

Different type of models and number of grids, were studied. Finally in a grid with dimensions (400 × 3148) of the type H-O, the independency of the grid, is approved as shown in Fig. 6.

It is worth to say that the equations of momentum and energy are discretized in-second order upwind method and also SIMPLE algorithm is used to solve velocity and pressure simultaneously. Accuracy of results are obtained for the momentum and energy and radiation in the orders 6E-10 and 8E-10 and 8E-10 respectively [10].
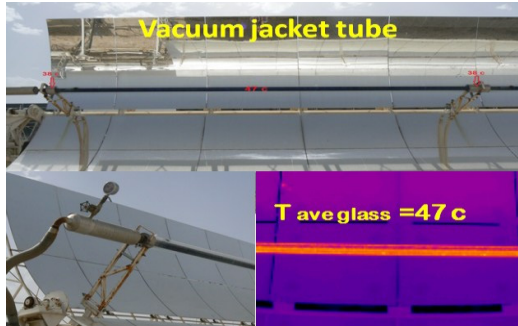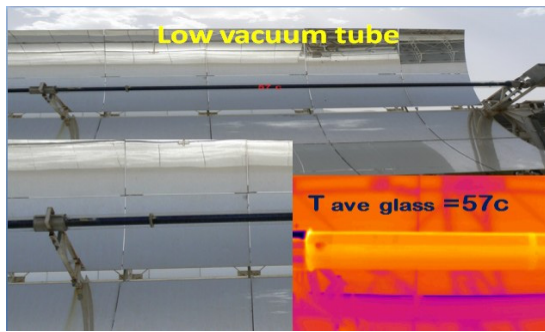

Fig. 5. IR-camera image of broken glass tube

Fig. 3. IR-camera image of vacuum jacket

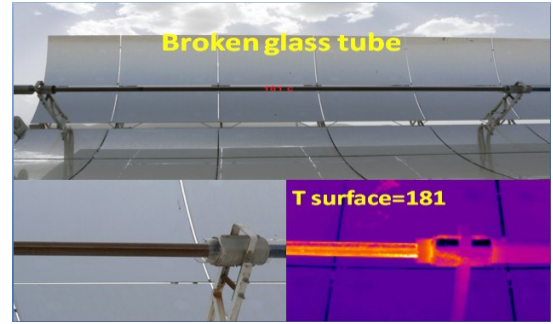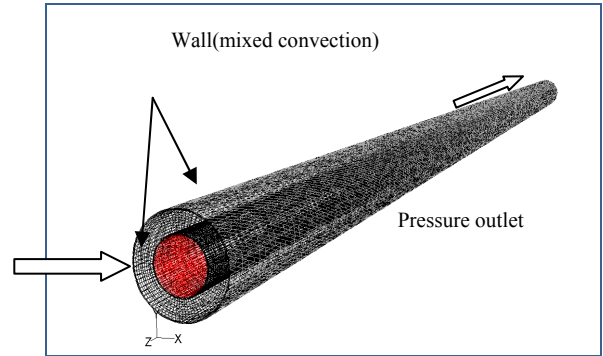
Fig. 6. The grid and boundary conditions, used in numerical solution
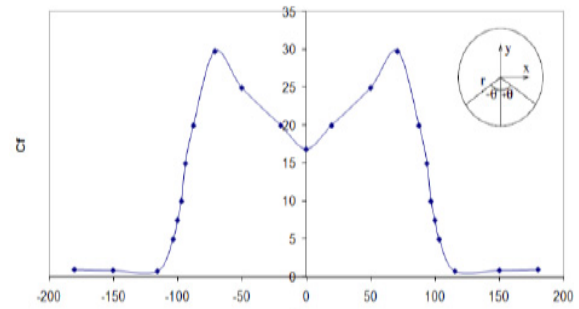

Fig. 4. IR-camera image of lost vacuum tube

Fig. 7. Local concentration ratio of shiraz parabolic trough collectors[8]

TABLE II: EXPERIMENTAL RESULTS FROM IR-THERMOGRAPHY METHOD FOR HEAT LOSS CALCULATION

	Vacuum jacket tube	Lost vacuum tube	Broken glass tube
date	2012/05/26	2012/05/26	2012/05/26
time	15:03	15:37	15:49
Inlet oil temperature (^{o}C)	206	204	200
Outlet oil temperature (^{o}C)	198	202	201
humidity	8.44	6.56	7.44
Sun angle	28.92	36.82	39.36
Direct intensity(W/m^2)	836	800	787
Ambient temperature(^{o}C)	33	33	33
Wind velocity(m/s)	1.5	1.5	1.5
Heat loss (W/m)	153.11	233.64	522.117

TABLE III: RESULTS OF NUMERICAL SOLUTION

	Broken glass tube	483.5	303	626.23	15.78	1.5	11.73	-	-
	Collector number	$T_{surf(ave)}$ (K)	T_{amb} (K)	Q_{loss} (W/m)	$U_{L(overall)}$ (W/m^2.k)	Wind velocity (m/s)	Outside heat transfer coefficent	T_{min} glass (K)	T_{max} glass (K)
numerical	Vaccume tube	489.1	303	219.36	5.36	1.5	11.73	326	342
	Lost vaccume tube	487	303	288.86	7.15	1.5	11.73	332	347

TABLE IV: COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

	Vacuum tube(w/m)	Lost vacuum tube(W/m)	Broken glass tube(W/m)
Loss(experimental)	153.11	223.64	522.17
Loss(numerical)	219.36	288.86	626.23
Reflected energy into absorer tube	2842	2720	2675
Loss percentage (experimental)	5.3	8.2	19.5
Loss percentage (numerical)	7.7	10.5	23.4
Collectors performance(numerical)	61%	58.5%	46%

IV. RESULTS

Results of numerical solution are presented in Table III. Overall heat transfer coefficient is calculated from equation(5) [11]:

$$U_L\left(w/m^2-k\right)=\frac{Q_{loss}}{A_{abs}\left(T_{abs}-T_{amb}\right)}\tag{5}$$

where Q loss is the amount of heat loss, A_{abs} is absorber area and T_{abs}, T_{amb} are absorber outer surface temperature and ambient temperature. Figs. 8-9 present the cross sectional temperature contours in middle of the vacuum jacket tube and the lost vacuum jacket tube.

As illustrated in Fig.10 glass envelope temperature for the lost vacuum tube is much higher than for vacuum jacket tube which results in higher heat dissipation rate.

Calculations from experimental measurments and the numerical solution are compared in Table IV.

Table IV shows that the amount of heat loss for numerical solution is higher than experimental measured data. The main reason which must be taken in to account is, defocusing collectors during experimental measurements which lead to lower glass envelope surface temperature in comparison with a tracking collector. Glass surface temperature calculated by the numerical solution is about 5-8 degree centigrade higher than experimental measured values. Collectors performance reduced considerably when the glass cover was removed or broken.
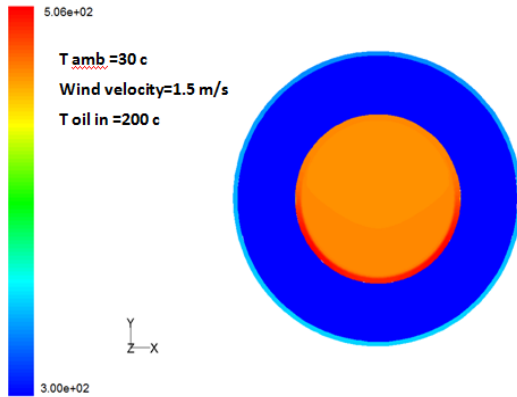

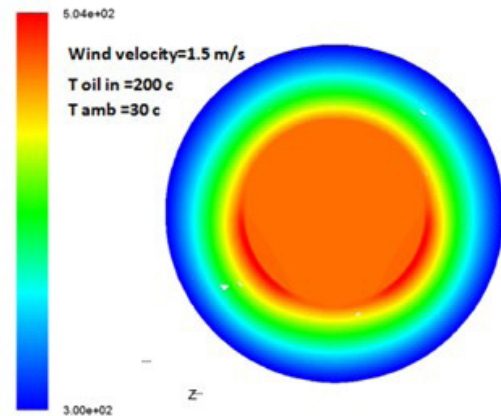Fig. 8. Contour of temprature in the middle of vacuum jacket tube

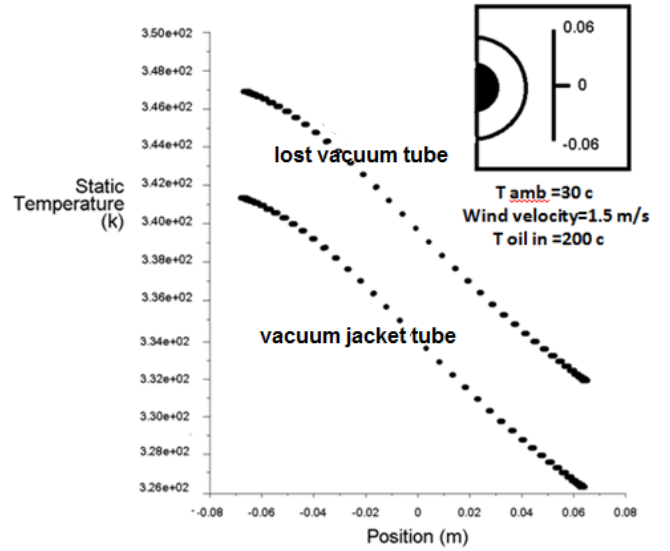Fig. 9. Contour of temprature in the middle of lost vacuum tube

Fig. 10. Comparison of vacuum jacket tube and lost vacuum tube glass envelope surface temperature

V. CONCLUSION

It is observed that from numerical and experimental analysis of heat loss of absorber tubes of Shiraz parabolic trough collectors:

1) The heat loss of lost vacuum tube is 40% higher than vacuum jacket tube, which leads to 3-5% reduction in the collector thermal performance.

2) The amount of heat losses for broken glass tube has a considerable increment. Numerical calculations show 12-16% reduction in thermal performance for broken glass tube.

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