MULTIVARIABLE GENERALIZED PREDICTIVE TEMPERATURE CONTROLLER DESIGN FOR YAZD SOLAR POWER PLANT

Abdolvahed Saidi[1] and Hamid D. Taghirad[2]

[1]Department of Engineering- Islamic Azad University of Saveh- Saveh- Iran
[2]Department of Electrical Engineering- K.N.Toosi University of Technology- Tehran- Iran

ABSTRACT

The Yazd Integrated Solar Combined Cycle (ISCC) Power Plant consists of two gas turbines that are generating power synchronous to Iranian national electrical network. One steam turbine will be supplied by gas units, while a parabolic through solar field is integrated with the system, as a combined cycle. In this paper an integrated model of the solar field with the purpose is presented, and a multivariable generalized predictive temperature controller is proposed for the system. As it is illustrated in the simulation results, such a control strategy can robustly regulate both the temperature of outlet oil, and the temperature of outlet steam water of the solar boiler, despite the variation of the inherent time delays of the system and external disturbances.

KEY WORDS

ISCC power plant, Solar Field, heat exchanger, modeling, multivariable GPC .

NOMENCLATURE

ρ_s	(kg/m^3) Density of oil pipe	A_f	Inner cross area of oil pipe (m^2)
$q^\bullet$	(m^3/s) Oil flow	T_f	Oil temperature along one collector (^{o}C)
C_s	Specific thermal capacity of oil pipe (J/kg ^{o}C)	$T_{\underline{f}}$	Oil temperature along previous collector (^{o}C)
G	Width of collector (m)	T_s	Temperature of oil pipe (^{o}C)
A_s	Area of metal pipe (m^2)	η_{opt}	Optical efficiency of mirrors
H_t	Heat transfer coefficient from pipe to oil (W/m^2 ^{o}C)	x	Distance of sensor from control valve (m)
ρ_f	Density of oil (kg/m^3)	H_L	Thermal loss coefficient (W/m^2 ^{o}C)
L	Inner diameter of oil pipe (m)	v	Oil velocity (m/s)
C_f	Specific thermal capacity of oil (J/kg ^{o}C)	ρ	Fluid density(kg/m^3)
I	**(W/ m^2)Sun direct radiation**	Q	Flow (m^3/s)
V	**Volume of fluid path (m^3)**	A	Cross area of fluid pipe (m^2)

$\overset{\bullet}{m}$ Mass flow of fluid(kg/s)

1. INTRODUCTION

The feasibility studies and technical specification of an integrated solar combined cycle power plant has been recently completed, and this type of power plant will be constructed in the city of Yazd in near future [15]. This power plant is designed with two steam turbines, two gas turbines and a solar field which supplies excess steam for steam turbines. The solar field consist of parabolic through collectors, solar boiler, pumps, control valves and an expansion vessel. The solar field itself possess 84 loops with eight collectors in each loop[16]. The collector has parabolic mirrors which focus the sun beams directly on the oil pipe, and the solar collectors are equipped with a sun tracker system. The oil enters the solar field with the temperature of 230°C and depart from it with the temperature of 391°C. The outlet oil from solar field enters a special heat exchanger named solar boiler, in which the accumulated heat in the solar field exchanges the supplied water into superheated steam[17].

The solar boiler consist of three exchangers that preheating, evaporating and superheating the water in three stage. The oil enters the superheater stage at 391°C/15bar and depart from preheater stage at 293°C/11bar. The supplied water enters the preheater with 235°C/105bar and depart the superheater with 380°C/102 bar. The inverse direction heat exchanger is chosen in order to increase the rate of heat transfer. The necessary pressure for oil is provided with 3 pumps, which one of them is standby. The type of tank in the solar field is an expansion vessel that the inlet pressure is fixed with nitrogen. The control valves are regulating the oil flow for temperature control. Figure (1) illustrates the schematics of an ISCC power plant [12].

2. SOLAR FIELD MODELING

In order to have a tractable and complete model of the solar field it is necessary to model the heat exchanger and the solar collectors in detail [1]. In this section the proposed models for these components are studied.
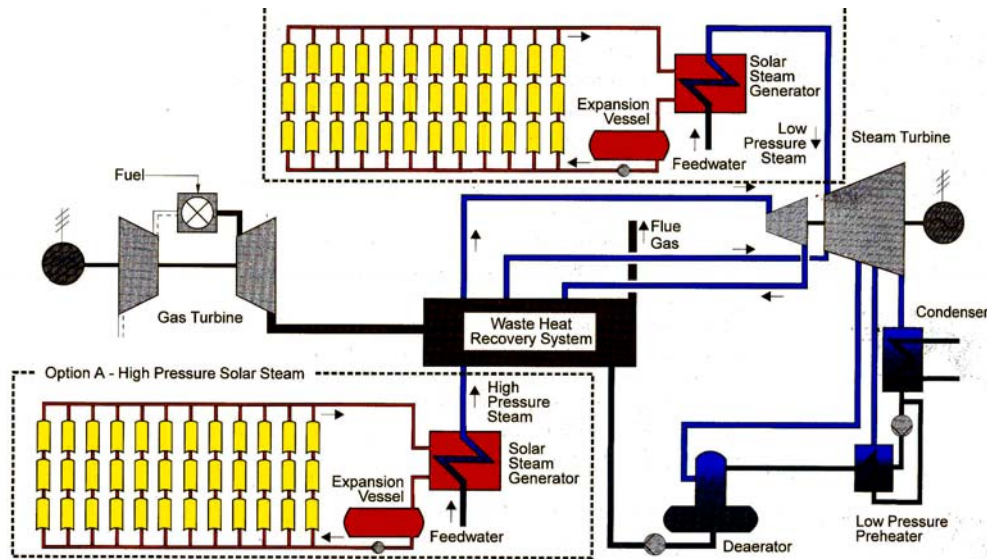

Figure 1: Integrated Solar Combined Cycle Power Plant

2.1 SOLAR COLLECTOR MODEL

The designed solar collector consists of double steel/glass pipe with vacuum insulation. The collector mirrors absorb a fraction of solar beam energy, and focuses the rest on the aforementioned oil pipes at the center of parabolic through. The heat energy is transferred to the oil through convection, conduction and radiation [14].
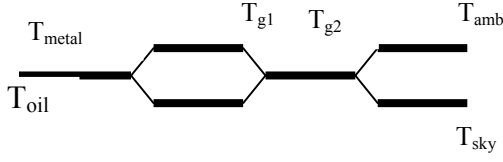
Figure 2- circuit model of heat transfer

Since the radiation heat transfer relates the rate of heat transfer to the power four of the temperature, in order to compensate for the temperature losses, a global coefficient of thermal losses is defined as below:

$$(1) \qquad H_l = \frac{Q_{loss}}{(T_s - T_{amb})}$$

In which T_s and T_{amb} are the oil pipe surface and the ambient temperatures, respectively. The Heat loss factor, H_l can be obtained from calibration experiments, and can be assumed constant with a sufficient degree of accuracy. Considering the heat loss in the collectors as elaborated, the dynamic equation of solar field heat transfer is given as following [4]:

$$(2) \qquad \rho_s C_s A_s \frac{\partial T_s}{\partial t} = \eta_{opt} IG - H_l G(T_s - T_{amb}) - LH_t(T_s - T_f)$$

This equation contains the absorbed energy of the oil pipe, the transferred energy to the oil and the heat loss to ambient. The left hand side of the equation determines the temperature variation of the metal pipe surface, in the condition while the thermal equilibrium has not been reached. The first term in the right hand side determines the volume of radiation energy that oil pipe has received, the second term shows the ambient heat loss, and the third term evaluates the oil absorbed energy. The amount oil absorbed energy can be determined by the following [4]:

$$(3) \qquad \rho_f C_f A_f \frac{\partial T_f}{\partial t} + \rho_f C_f q^\bullet \frac{\partial T_f}{\partial x} = LH_t(T_s - T_f)$$

In this equation the first term in LHS governs the temperature variation of the oil with respect to time, and the second term governs the temperature variation with respect to the movement of oil. Since the governing heat transfer equations are partial differential equations, for the purpose of control they are discretized with the assumption of the temperature being fixed along each collector, using finite element method.

$$\frac{\Delta T_s}{\Delta t} = \frac{\eta_{opt}.G}{\rho_s C_s A_s} I - \frac{K}{\rho_s C_s A_s}(T_s - T_{amb}) - \frac{K_1}{\rho_s C_s A_s}(T_s - T_f)$$

(4)

$$\frac{\Delta T_f}{\Delta t} = \frac{m^\bullet}{\rho_f A_f}(T_f - T_{f^-}) + \frac{LH_t}{\rho_f C_f A_f}(T_s - T_f)$$

2.2 HEAT EXCHANGER MODEL

In order to model the heat exchanger, the inlet pressure is assumed to be constant [12,14]. The governing equations can then be classified into two set of equations for temperature variations and phase variations. It is assumed that in the preheater and superheater stages, there are no phase change, and hence, the governing equations are due to the temperature variation. In the preheater there is only temperature rise in water, while is superheater the temperature increase occurs on the steam [17]. The boiler design conditions guarantees that the water is entering the preheater with the temperature of 293°C and will depart it with the temperature of 314°C. In steam generator water exchange to steam with the temperature of 314°C and in superheater saturated steam is heated to the temperature of 380°C. Note that the governing equation of heat exchanger is also in the form of partial differential equation. For control purpose the governing equations are discretized using finite element method with three nodes. The governing equation of oil behavior in each node is as follows [13, 18]:

3

$$\rho_{oil}V_{oil}C_{oil}\frac{dT_{oil}}{dt} = \rho_{oil}C_{oil}F_{oil}(T_{oil(out)} - T_{oil(in)})$$

$$(5) \qquad -\frac{K\left[(T_{oil(out)} - T_{water(out)}) - (T_{oil(in)} - T_{water(in)})\right]}{Ln\left(\dfrac{T_{oil(out)} - T_{water(out)}}{T_{oil(in)} - T_{water(in)}}\right)}$$

the left side sentence of above equation show the temperature variation of oil in time, the first sentence of right, show the temperature variation of oil in effect of moving oil between pipes of energy absorber in any stage. The second sentence of right side shows the rate of heat transfer from oil to water. The equation that gives the thermo dynamical behavior of water (steam) in pre heater and super heater is shown as equation (6).

In which it is assumed that the temperature in those stages are fixed and only temperature variations occurs at the transient of one stage to another. Similarly, the equation that gives the thermo-dynamical behavior of water (steam) in preheater and superheater in this case, is [13, 18]:

$$\rho_{water}V_{water}C_{water}\frac{dT_{water}}{dt} = -\rho_{water}C_{water}F_{water}(T_{water(out)} - T_{water(in)})$$

$$(6) \qquad +\frac{K\left[(T_{oil(out)} - T_{water(out)}) - (T_{oil(in)} - T_{water(in)})\right]}{Ln\left(\dfrac{T_{oil(out)} - T_{water(out)}}{T_{oil(in)} - T_{water(in)}}\right)}$$

In equation (6) we assume that temperature in each section is fixed (temperature is variation just in cross from section to another section). It should be considered that in this equation, the physical characteristic of water in pre heater has been assumed fixed because of the small variation in these parameters.

In this equation the physical properties of the water is assumed to be fixed in the preheater. Whereas, the physical properties of steam in the superheater show larger variation, and hence, must be taken into account. To include this variation into the system dynamics the changes of C, ρ (density and specific thermal capacity) is considered by the following equations into the model. (For a detail discussion on the modeling refer to [6].

$$(7) \qquad \rho_{steam} = \frac{P}{RT} \qquad\qquad R = \frac{\overline{R}}{18}$$
$$\overline{R} = 8.3145 \quad (\frac{kN.m}{kmol.K})$$

$$(8) \qquad \overline{C} = 143.05 - 183.54\theta^{0.25} + 82.751\theta^{0.5} - 3.6989\theta$$

$$(9) \qquad C_{steam} = \frac{\overline{C}}{18.015}$$
$$\theta = T(Kelvin)/100$$

The equation that gives the thermo-dynamical behavior of saturated steam in steam generator is shown in equation (10):

$$(10) \qquad \frac{K_2\left[(T_{H1} - T_{C2}) - (T_{H2} - T_{c1})\right]}{Ln(\dfrac{T_{H1} - T_{c2}}{T_{H2} - T_{c1}})} = m_o^\bullet h_o - m_i^\bullet h_i + (m_{cv}u)^\bullet$$
$$m_o^\bullet = m_i^\bullet - m_{cv}^\bullet$$

In this equation $m_i^\bullet, m_o^\bullet, m_{cv}^\bullet$ are flow of inlet water, flow of outlet water and variation of control value. h is enthalpy of steam and u is energy of mass unit. The left side sentence of above equation is rate of heat transfer from oil to water. The first two sentences of right, show the variation of thermal power of saturated steam in cross of control value, and last sentence show the variation of energy in control volume [9, 10].

3. CONTROLLER SYNTHESIS

The solar field is a nonlinear, multivariable system possessing long and varying time delays. For this class of systems the predictive control methods are suitable. These types of controller are the most attractive controllers for process control practitioners, after common PID controllers [3, 7]. In this paper a multivariable GPC routine is proposed for temperature control of the system. The time delay in the system is caused by the installation distance (x) between the actuators and the sensors in the system. Hence, the time delay is related to the fluid speed and distance between the sensor and pump, as follows:

$$\tau = \frac{x}{v}$$

(11) $$m^{\bullet} = \rho Q = \rho A v \Rightarrow v = \frac{m^{\bullet}}{\rho A}$$

$$\Rightarrow \tau = \frac{\rho A x}{m^{\bullet}} = \frac{\rho V}{m^{\bullet}} = \frac{\sum \rho_i V_i}{m^{\bullet}}$$

3.1 SYSTEM IDENTIFICATION AND PARAMETER ESTIMATION

The solar field is a two-input two output system, from a control point of view. The system inputs are the oil and water flow rates and its outputs are the oil and water temperatures. From the well known identification techniques, the transfer matrix of the system can be obtained from simulated input output pairs of the system. The identified model of the system has been derived as following:

(12) $$G'(z^{-1}) = \begin{bmatrix} \dfrac{k_{11}z^{-1}}{1+T_{11}z^{-1}}z^{-d_{11}} & 0 \\ \dfrac{k_{21}z^{-1}}{1+T_{21}z^{-1}}z^{-d_{21}} & \dfrac{k_{22}z^{-1}}{1+T_{22}z^{-1}}z^{-d_{22}} \end{bmatrix}$$

As it is clear from the structure of the identified model, the water temperature is almost not related to the outlet oil temperature ($G_{12}=0$), and this weak relation can be modeled as a disturbance to the system. The other components are simply modeled with a first order system with a time varying time delay. This structure of the model can be used for the GPC synthesis.

3.2 DESIGN OF MULTIVARIABLE GPC CONTROLLER

The controller design consists of three steps. A) prediction model determination. B) Objective function assignment and C) control law calculation. The prediction model for the system can be derived from equation (12), in which the model is rewritten in the form of :

(13) $$A(q^{-1})y(t) = B(q^{-1})u(t-1) + \frac{e(t)}{\Delta}$$

In which $u(t)$ is control signal and $y(t)$ is the process output as the vector of oil and water temperatures. Moreover, $e(t)$ is measurement noise with zero mean and $\Delta = 1 - q^{-1} . A(q^{-1})$, $B(q^{-1})$ are the polynomial matrices with degree n_A and n_B respectively. The Objective function to be minimized has the form of :

(14) $$J = \sum_{i=1}^{m} \left\{ r_i \sum_{j=1}^{N_2} [y_i(t+j) - w_i(t+j)]^2 + \lambda \sum_{j=1}^{N_u} [\Delta u(t+j-1)]^2 \right\}$$

Or in matrix form:

(15) $$J = [y-w]^T R[y-w] + \lambda \Delta u^T \Delta u$$

In which N_2 is the maximum of prediction horizon and N_u is the control horizon. λ is the penalty coefficient and R is the weighting matrix of errror signal. In order to generate the control signal, the future outputs of the system is predicted by the following equation:

(16) $$\hat{y} = G\Delta u + f$$

In which, f is the free response of the system and G includes the step response parameters. The optimal solution for the control signal to minimize the cost function (15), while preserving closed loop stability is calculated from the following equation.

$$(17) \quad \Delta u = \begin{bmatrix} I & 0 & \cdots & 0 \end{bmatrix} \begin{bmatrix} G^T R G + \lambda I \end{bmatrix}^{-1} R G^T (w - f)$$

3.3 PARAMETER TUNING IN MULTIVARIABLE GPC

The tuning of the controller parameters is mostly based on experience, and the simulation of the closed loop response. The designer has the freedom to tune either the cost function weighting, or change the disturbance dynamics, observer dynamics, the desired trajectory and finally the prediction and control Horizons. More penalizing λ on the control effort and R on the tracking error will reduce the control effort. The structure of the model is fixed in this method and only the noise levels can be assigned to tune the performance. However, from the inherent integrstor form of $D(z^{-1}) = (1 - z^{-1}) A(z^{-1})$ forces the error of the closed loop system to a step disturbane to converge asymptotically to zero [8, 11].

4. CLOSED-LOOP SIMULATION RESULTS

The designed controller for the system has the parameters $N_1 = 6$, $N_2 = 37$, $N_u = 3$ and the weighting functions are tuned through the simulation to:

$$Q_i = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad R_i = \begin{bmatrix} 3.5 & 0 \\ 0 & 0.2 \end{bmatrix}$$

Moreover, the time delays for the oil and water is calculated from the design condition (NDI=900 w/m^2) and the system pipe length to constant values of 35 and 50 times the sampling time, respectively. The time constant of the system model is identified to be ten seconds. The closed loop response of the system using GPC controller is compared to that using PI controller with controller gains: $k_p = 0.04$, $k_i = 0.007$. The variation of solar radiation is considered as a constant disturbance and illustrated in figure (3). In this simulation the solar radiation is changed from 900 to 800 w/m^2 and its effect on the oil and water temperature is illustrated in figure (3). Due to the larger time delays in oil path compared to that in the water path, the water temperature output shows a faster response. However, both oil and water temperatures are rejecting the effect of disturbance with PI and GPC controllers. Although the overall performance of two controllers are relatively desirable the coupling of two quantities have greater impact on the PI controller compared to that on GPC design.
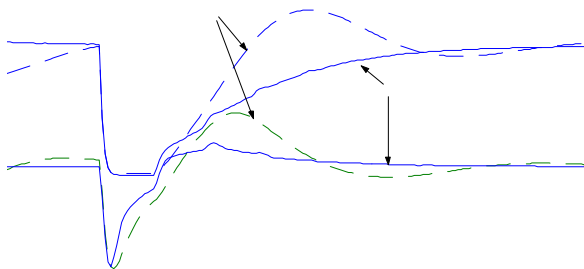

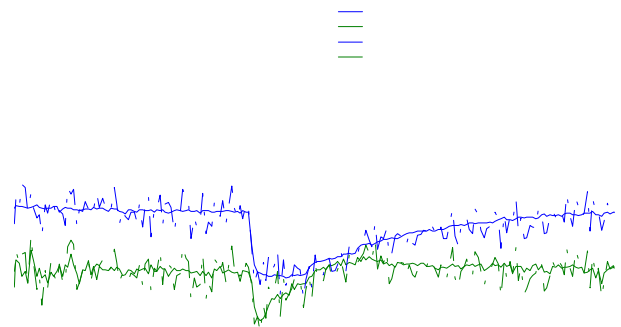Figure 3- The effect of solar radiation on the response

Figure 4- The effect of measurement noise on the response

In figure (4) the effect of measurement noise is illustrated on the response. GPC controller is effectively rejecting the noise effect, due to its predictive nature.

Figure (5) illustrates the effect of leakage in oil and water pipes. In this case it is assumed that the oil leakage occurs on the path before entering the solar field and the water leakage occurs before entering the heat exchanger. Due to this failure in the system the temperature of oil and water is observed just after the leakage happens. However, the controller is able to regulate the temperature, in spite of the failure. The superior performance of the GPC controller is also observed in this simulation. Figure (6) illustrates the change in the system delay as a result of flow rate change due to the leakage. It is observed that the system delay increases as the flow rates increased, as expected.

5. CONCLUSIONS

In this paper a multivariable predictive control algorithm is proposed for the solar power plant. It is shown that due to the existance of large and variable time delays in the temperature outputs of the heat exchanger of the power plant, and the coupling between the oil and water temperature of it, a multivariable GPC controller is effectively regulating the system outputs, despite disturbances, measurement noise, and leakage. The predictive structure of the controller make it less sensitive to the varying time delays. The proposed controller is able to not only preserve the stability of the system, but also the performance of the system with the presence of disturbance and measurement noise is desirable.
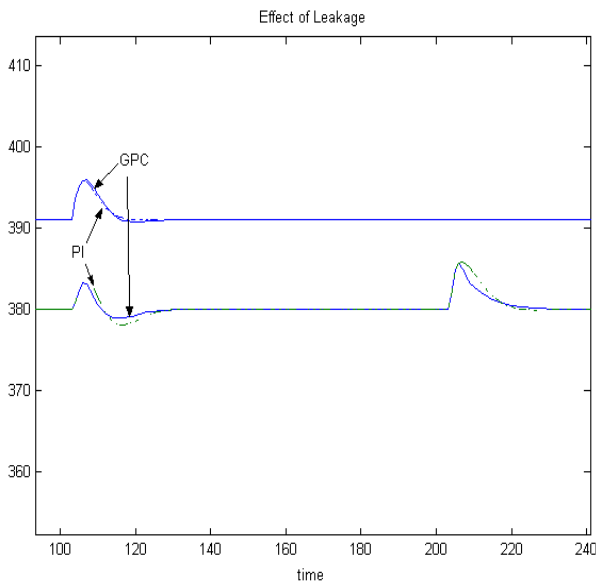

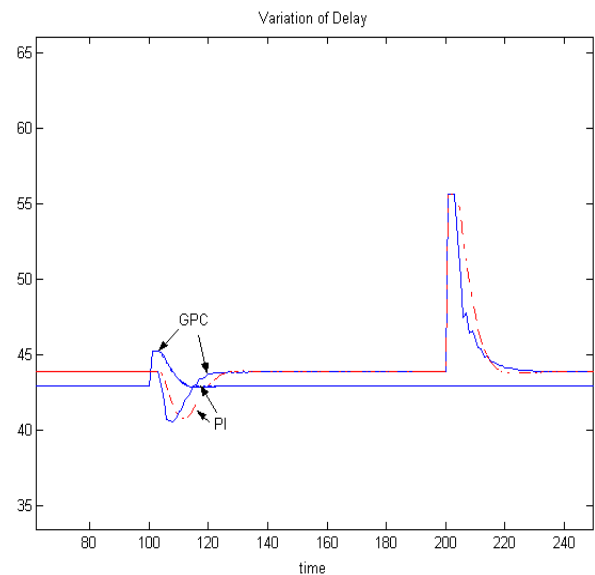Figure 5- The effect of leakage on oil and steam temperature

Figure 6- The Variation of delay in effect of flow variation

REFERENCES

A.W. ordys – A.W. pike - M. A. Johnson – R.M.katebi and M.J.Grimble."Modeling and simulation of Power Generation Plants" Springer-verlag 1994   [1]

E.F Comacho – M. Berenguel and F.R. Rubio. "Advanced Control of Solar Plant" Springer-verlag 1997   [2]

E.F.Camacho and C.Bordons "Model Predictive Control in the Process Industry" Springer-Verlag,1995   [3]

Gordon van wylen- Richard Sonntag- claus Borgnakke "Fundamentals of Classical Thermodynamics" fourth Edition   [4]

J.E. Marshall "Control of time – delay systems." Institution of Electrical Engineers 1979 [5]

J.M.Maciejowski "Predictive Control with constraint" Prentice Hall-2002 [6]

Pierre Bélanger "Control engineering: a modern approach" Saunders College Pub.1995. [7]

V.Ganapathy "Steam Plant Calculation Manual." Marcel Dekker1984 [8]

Donna M.Schneider "Control of Process with Time Delays" IEEE Transactions on Industry Applications Vol.24No.2,March/Appril-1988 [9]

O.Bego,N.Peric "Decoupling Multivariable GPC with Reference Observation" 10th Mediterranean Electrical Conference, MeleCon 2000,Vol. II [10]

A.Saidi "Solar Field Modeling and Temperature Control of Yazd ISCC Power Plant" Master thesses, K.N.Toosi,University of technology,2002 [11]

Jonas Eborn and Karel Johan Astrom. "Modeling of a Boiler Pipe with Two-Phase Flow Instabilities" www.control.lth.sel~kja/rodpaper.pdf [12]

K.J Astrom – R.D. Bell. "Drum – Boiler Dynamics"1998 www.control.lth.sel~kja/rodpaper.pdf [13]

Sandia Co." Test Results SEGS LS-2 Solar Collector" Technical Report www.Sandia.gov. 1994 [14]

S.R.Hosseini " Report of feasibility study (Technical and Economical) of yazd solar thermal power plant" NRI.2000 [15]

S.R.Hosseini " Report of solar field design in yazd solar thermal power plant" NRI.2000 [16]

S.R.Hosseini " Report of solar boiler design in yazd solar therma power plant" NRI 2000 [17]

Pilkington (Solar International) "Status Report on Solar Thermal Power Plants". www. Pilkington .com [18]