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EFFECT OF HEAT RECOVERY STEAM GENERATOR TYPE ON THE EFFEICNCY OF INTEGRATED SOLAR COMBINED POWER PLANT

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Abstract

This paper study the effect of Heat Recovery Steam Generator (HRSG) type on the thermal effeicncy of Integrated Solar Combined Power Plant. The aim of this work is to improve thermal effeicncy of Integrated Solar Combined Cycle System (ISCCS). In this plant, recovery the largest possible amount of thermal energy in flue gases of gas power plants, to produce steam, and adopting solar energy to produce hot water. The efficiency of Solar Integrated Steam Power Plant can be increased from 40% for case A to 50% for case B, due to increased the aviable heat of HRSG from 168.27 MW to306 MW. Also, thermal environmental pollution can reduced from 148.36 ℃ to 68.97 ℃.

Keywords : Heat Recovery Steam Generator, Solar Energy, Integrated Solar Combined Power Plant.

I. Introduction

The power plant is a machine used to convert the mechanical energy to electrical energy, by the turbine, which consists of a set of blades run in a certain way, the turbine is connected to a shaft that moves the movement from it to the generator. There are many types of power plants that differ from each other, depending on the operating way of the turbine. These plants are divided into four types: Steam turbine plant depending on the type of fuel is used (Fossil fuels, Nuclear, Geothermal, Solar heat steam), Hydro turbines plant depending on rivers, dams and pump storage, Gas turbine plant and Wind turbine plant. The Combined power plant consists of steam turbine plant and Gas turbine plant, the available power in the exhaust gases of the gas turbine plant is used, to heat the feed water in steam turbine power plant, by using the model of the Heat Recovery Steam Generator (HRSG). Where the fuel is used only in the gas plant. Sometimes the power in the flue gases to generate steam is not enough, so used solar energy to fill the deficit, in this case, the plant is called integrated solar combined power plant. The thermal performance of this plant was studied by several scholars. Study the performance of the solar-assisted KCS11 with constant turbine pressure is equal to 17.53 bar, show that this plant has more efficiency and net output than the standalone KCS11, and reduce the emission of CO_2 about 1008.28 t and reduce the exit temperature of the flue gases about 10K[V]. Compared the integrated solar combined power plant with a combined power plant, to analysis the environmental and the economic performance effects, found the integrated solar combined power plant has lower CO_2 emission and fuel consumption than the combined power plant [VI]. Also, reduce the environmental affect by 3.8%, and increase the net output by 4.2 %, by study the solar energy effect on the combined power plant [II]. Found the best integration, by study the system performance of different types of solar technologies integrated with a combined power plant, found the solar efficiency of a parabolic trough, linear Fresnel, and central receiver is 61.2%, 58%, 56.2%, respectively [VII]. Study the levelized energy cost (LEC) of three cases of solar system integrated with combined power plant (ISCCS): solar thermal system with a direct steam generator (DSG), a solar thermal system with heat transfer fluid (HTF), and solar electric generator system. Found the case with DSG is the suitable option due to it has LEC lower than the other cases because increasing the net efficiency of it [VIII]. Study the performance of two types of solar collector (the evacuated tube collector, and concentering solar collector) integration with a combined power plant, found integrated both the evacuated tube and concentrating solar collector with integrated solar combined cycle (ISCC) system has higher efficiency than the concentrated solar collector only[XIV]. Prove the purpose of using HRSG is to raise turbine inlet temperature, by a used fraction of flue gases in HRSG, and the other fraction of flue gases in the heat exchanger (HE) located on other gas turbine cycle [XI]. Studied a solar thermal power plant (STPP) through three models: Solar electricity generation system (SEGS), Integrated solar combined cycle system (ISCCS) with heat transfer fluid (HTF) technology, and Integrated solar combined cycle system (ISCCS) with direct steam generation (DSG) technology. Results showed that thermal efficiency of ISCCS-HTF is higher than SEGS, due to the contribution of the gas turbine which raises the quality of generated steam. The right choice is ISCCS-DSG, because of levelized energy cost (LEC) for ISCCS-DSG is less than the two other methods[IX]. Developed an integrated Solar Aided Power Generation (SAPG) model. The efficiency of SAPG with different capacities (subcritical, supercritical, ultra-supercritical) units of the power plant is evaluated, by integrated different pressure stages of feedwater heaters to different temperature grades of solar heat.

Compared between three types of focusing collectors. Results showed SAPG technology can have higher conversion efficiency than solar power plant alone and is the most effective way to use solar energy in the supercritical and subcritical units than in ultra-supercritical units of the power plant.[XII] Designed and analyzed a model for the hybrid renewable energy system, to ensure generated stable power values with different conditions. Heat Recovery Steam Generator HRSG of this model consists of three parts: solar energy, wind energy, and Inter Phase Transformer IPT. Results showed the model produces an effective transformation with a voltage harmonic ration 0.69%, proved the efficiency in real-time.[III] Conducted a review of previous studies of the nonconventional and conventional integrated power plant, carried since the1970_s until 2013_s . Focused on three types of conventional power plant: Hybrid solar steam power plant, hybrid solar combined cycle power plant, hybrid solar gas turbine power plant. Results showed that the most successful option is integrated solar combined cycle system (ISCCS) given its advantages and plans for implementation ISCCS different in the world, like Egypt, Iran, Tunisia, and Spain because it is more economical.[XIII] In this work, the effect of two types of HRSG on Integrated Solar Combined Power Plant are compared, to enhanced thermal efficiency of Integrated Solar Combined Power Plant.

II. Solar Integrated Combined Cycle (SICC) configuration

The Solar Integrated Combined Cycle (SICC) plant consists of four main units: solar field, thermal power plant , gas power plant, Heat Recovery Steam Generator (HRSG), Heat Solar Steam Generator (HSSG). This case presents a combination of thermal power plant with the AL-Zafaraniyah gas power plant, then integrated with the solar field, as case A shown in Figure. (1), and case B shown in Figure(2). The boiler, in this case is replaced by Solar Hot Water Generator SHWG, and the Heat Recovery Steam Generator HRSG.The power in the flue gases is not enough, to generate steam, so used solar energy from solar field to fill the deficit, by using the model of the Heat Solar Steam Generator (HSSG).

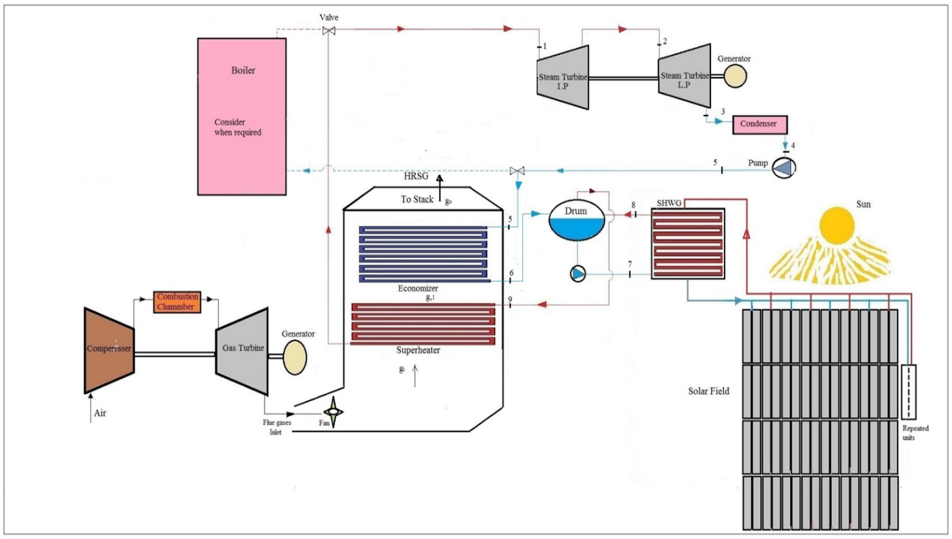

Figure .1. Case A

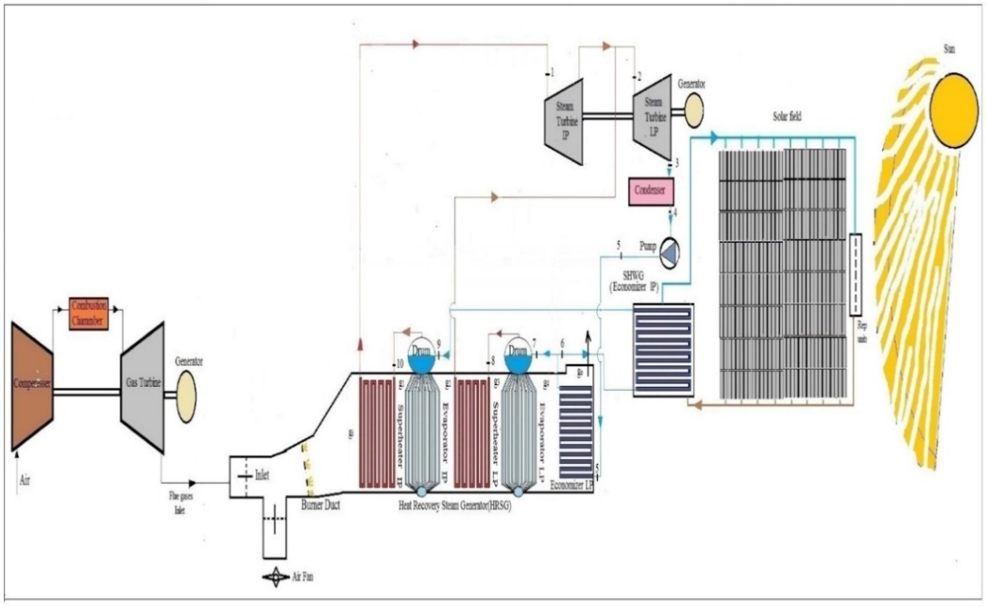

Figure .2. Case B

II.i Parabolic trough Collectors (PTC_S) Field

The concentrated solar heating system with oil as heat transfer fluid (HTF) consist of open number of trough solar collector units, each unit has eight reflectors in series connection with 9 m^2 aperature area . Number of unit in parallel connection depended on the solar energy required in Solar Hot Water Generator (SHWG).

II.ii Solar Hot Water Generator (SHWG)

The proposed Solar Hot Water Generator (SHWG) is used to heat the feed water in a thermal power plant to produce steam or hot water, as an evaporator in case A, shown in Figure (1), and as intermediate pressure economizer in case B, shown in Figure (2). In this case heat gain from concentrated solar collectors is used to reduce the amount of fuel consumption in the burner. Effectiveness (ε_{SHWG}) of SHWG is adopted as 0.69 [Calise et al. 2018], the thermal performance of SHWG is analyzed based on heat balance, at solar noon.

The number of solar collector units needed is calculated by :

$$Q_{sol} = \varepsilon_{SHWG}\ Q_{ga,o} \quad (1)$$

$$Q_{ga,o} = \text{No. of units} \times Q_{ga,s} \quad (2)$$

$$\text{No. of units} = \frac{Q_{ga,o}}{Q_{ga,s}} \quad (3)$$

where:

Q_{sol} is solar energy

ε_{SHWG} is effectiveness of SHWG.

$Q_{ga,o}$ is the total heat gain

$Q_{ga,s}$ is heat gain by single unit of collector, it is taken from experimental results (6878.2, 7198.5, 6203.1) W at noon for (8^{th} March, 9^{th}April, 5^{th}May) respectively.

II.ii.a case A

Referring to Figure (1) the heat absorbed by evaporator (Q_{evap}) is calculated as:

$$Q_{evap} = Q_{sol} = \overset{\circ}{m}_7 h_{fg,7} \tag{4}$$

where:

$\overset{\circ}{m}_7$ is the mass flow rate of the feedwater inlet to the evaporator (100 kg/s).

$h_{fg,7}$ is the enthalpy of evaporation (1795.7 kJ/kg) at pressure 3.1 MPa. Adopted data from table (1).

II.ii.b. Case B

Referring to Figure (2) and table (2), the heat absorbed by economizer ($Q_{econ,2}$) (IP) is calculated as:

$$Q_{econ,2} = Q_{sol} = \overset{\circ}{m}_6 C_{p,6}(T_{sat,2} - T_{sat,1}) \tag{5}$$

II.iii. Heat recovery steam generator (HRSG)

Two different types of Heat Recovery Steam Generator (HRSG) are analyzed in this plant. Unfired, natural circulation, single stage pressure HRSG is used in case A, shown in Figure (1), and firing duct natural circulation multi stages pressure HRSG, the theoretical model is used in case B, as shown in Figure (2).

These models are based on the following assumptions:

1. Steady state heat transfer processes within HRSG.
2. Thermophysical properties of exhaust gases and feedwater are constant.
3. Effectiveness (ε_{HRSG}) is adopted as 0.87 [Calise et al. 2018].
4. Flue gases are considered as an ideal gas.

The gas turbine plant exhaust gases flow rate ($\overset{\circ}{m}_g$) is 410.27 kg/s. [AL-Zafaraniyah plant]. The thermal performance of the heat recovery steam generator is analyzed, per heat balance.

II.iii.a. Case A

The available sensible energy (S) related to flue gases temperature of 538°C is equal to 245 Btu/Ib [Potter 1956]. Adopted data from table (1).

Heat absorbed by super heater (Q_{sup}) is calculated by:

$$Q_{sup} = \varepsilon_{HRSG}\, \dot{m}_g C_{p,g}(T_{gi} - T_{g,1}) = \dot{m}_{10} c_{p,10}(T_1 - T_{sat}) \quad (6)$$

Heat absorbed by economizer (Q_{econ}) is calculated as:

$$Q_{econ} = \varepsilon\, \dot{m}_g C_{p,g}(T_{g,1} - T_{g,o}) = \dot{m}_5 C_{p,5}(T_{sat} - T_5) \quad (7)$$

Table -1: Operational condition of Case A

1	**Gas turbine plant**					
	Flue gases temperture	$\dot{m}_g$	$C_{p,g}$			
	538 °C	410.27 kg/s	1214.37 J/kg. K			
2	**Steam turbine Plant**					
	$\dot{m}_1$	Pressure of turbine (MPa)				
	100 kg/s	IP	LP			
		3.1	0.37			
3	**SHWG**					
	Evaporator (evap)					
	$\dot{m}_7$	$h_{fg,7}$				
	100 kg/s	1795.7 kJ/kg				
4	**HRSG**					
	Superheater (sup)				**Economizer (econ)**	
	$\dot{m}_9$	$C_{p,9}$	T_1	T_{sat} at pr. (3.1) MPa	T_5	$C_{p,5}$
	100 kg/s	3.43 kJ/kg°C	500°C	235.72 °C	50°C	4.18 kJ/kg. °C

II.iii.b. Case B

The available sensible energy (S) related to flue gases temperature of 742.4°C is equal to 340 Btu/Ib [Potter 1956]. Adopted data from table (2).

Analysis of the HRSG in five stages:

1. Heat absorbed by super heater ($Q_{sup,2}$) (IP) is calculated by eq. (6), but $T_{sat,2}$ instead of T_{sat}.
2. Heat absorbed by evaporator ($Q_{evap,2}$) (IP) is calculated as:

$$Q_{evap,2} = \dot{m}_g C_{p,g}(T_{g1} - T_{g2}) = \mathring{m}_9 \times h_{fg,9} \tag{8}$$

3. Heat absorbed by super heater ($Q_{sup,1}$) (LP) is calculated as:

$$Q_{sup,1} = \dot{m}_g C_{p,g}(T_{g2} - T_{g3}) = \mathring{m}_8 c_{p,8}(T_2 - T_{sat,1}) \tag{9}$$

4. Heat absorbed by evaporator ($Q_{evap,1}$) (LP) is calculated by

$$Q_{evap,1} = \dot{m}_g C_{p,g}(T_{g3} - T_{g4}) = \mathring{m}_7 \, h_{fg,7} \tag{10}$$

5. Heat absorbed by economizer ($Q_{econ,1}$)(LP) is calculated as:

$$Q_{econ,1} = \dot{m}_g C_{p,g}(T_{g4} - T_{g,o}) = \mathring{m}_5 C_{p,5}(T_{sat,1} - T_5) \tag{11}$$

Table – 2: Operational condition of Case B

1	**Gas turbine plant**						
	Flue gases temperture	$\dot{m}_g$	$C_{p,g}$				
	742.4°C	411.27 kg/s	1274.34 J/kg. k				
2	**Steam turbine Plant**						
	$\mathring{m}_1$	Pressure of turbine (MPa)					
	100 kg/s	IP	LP				
		4.6	0.7				
3	**SHWG**						
	IP	**Economizer (econ,2)**					
		$T_{sat,2}$ at pr.(4.6)MPa	$T_{sat,1}$ pr.(0.7)MPa	$C_{p,6}$	$\mathring{m}_6$		
		258.8 °C	164.97°C	4.35kJ/kg °C	82 kg/s		
4	**HRSG**						
	IP	**Superheater (sup,2)**				**Evaporator (evap,2)**	
		$\mathring{m}_{10}$	$C_{p,10}$	T_1	$T_{sat,2}$ at pr. (4.6) MPa	$\mathring{m}_9$	$h_{fg,9}$ at pr. 4.6 MPa

		82 kg/s	4.03 kJ/kg°C	500°C	258.8 °C	82 kg/s	1669 kJ/kg			
	LP	**Superheater (sup,1)**				**Evaporator (evap,1)**		**Economizer (econ,1)**		
		$\mathring{m}_8$	$C_{p,8}$ at $T_{sat,1}$	T_2	$T_{sat,1}$ at pr. (0.7) MPa	$\mathring{m}_7$	$h_{fg,7}$ at pr. (0.7) MPa	T_5	$C_{p,5}$	$\mathring{m}_5$
		18 kg/s	2.45 kJ/kg°C	260°C	164.97 °C	18 kg/s	2066.3 kJ/kg	50 °C	4.18 kJ/kg. °C	100 kg/s

III. Approach and Pinch points of HRSG

The approach and the pinch points of HRSG are adopted to design this element. The pinch point range is (5-15)°C, it can be considered in HRSG design with conditions:

III.i Case A

$T_{g,1} > T_{sat}$

$T_{g,o} > T_5$

The flue gases temperature outlet from HRSG in this option can be calculated by:

$$T_{g,o} = T_{g,1} - R(T_{sat} - T_6) \quad (12)$$

III.ii Case B

$T_{g,2} > T_{sat,2}$

$T_{g,4} > T_{sat,1}$

$T_{g,o} > T_5$

The flue gases temperature outlet from HRSG in this option can be calculated by:

$$T_{g,o} = T_{g4} - R(T_{sat,1} - T_5) \quad (13)$$

IV. Integrated Solar Combined Power Plant efficiency

The thermal efficiency of this system is defined as [Li, et al 2018]:

$$\eta_{th} = \frac{W_{net}}{\eta_b Q_{ff} + Q_{sol}} \quad (14)$$

where,

W_{net} the network is the total net output power from gas turbine and the thermal power plant (MW). Thermal power plant (N_{st}) is calculated by

$$N_{st} = W_{Tur} - W_{Pump} \tag{15}$$

Q_{ff} is the thermal energy resulted by burning fuel (MW). It is calculated by

$$Q_{ff=} \quad _{ff}\,HV \tag{16 }$$

HV is the heating value of heavy fuel (41204.74 kJ/kg), m_{ff} is the mass flow rate of heavy fuel (9.7 kg/s). η_b is the burner efficiency (0.75).

IV.i. Case A

The work of the steam turbine W_{Tur} (MW) is calculated by:

$$W_{Tur} = \mathring{m}_1 (h_1 - h_3) \tag{17}$$

The work of the pump W_{Pump} (MW) is calculated as:

$$W_{Pump} = \mathring{m}_4 (h_5 - h_4) \tag{18}$$

IV.ii. Case B

The work of the steam turbine W_{Tur} (MW) is calculated by:

$$W_{Tur} = \mathring{m}_1 (h_1 - h_2) + \mathring{m}_2 (h_2 - h_3) \tag{19}$$

The work of the pump W_{Pump} (MW) is calculated by eq. (18)

V . Results and Discussions:

The Integrated Solar Combined Power Plant (Case A) improved the efficiency of power plant from 35.6 % for gas power plants to 40 % for integrated solar combined power plant, according eq. (14). This plant saves the fuel consumption in the burner of thermal power plant to produce steam, and proved network is 192.83 MW. The work obtained from steam turbine is equal to 86.51 MW according eq.(17). The boiler in this plant is replaced by HRSG to proved 168.27 MW to produce steam, and reduce the temperature of flue gases outlet to surrounding from 538 ℃ to 148.36 ℃ . SHWG to proved 179.57 MW, the heat need in the evaporator. The efficiency of the Integrated Solar Combined Power Plant (CaseB) improved to 50 % , and proved network is 182.66 MW **.**The work obtained from steam turbine is equal to 75.66 MW. HRSG proved 306 MW, to produce steam, and to reduce the flue gases temperature outlet to surrounding from 538 ℃ to 68.97 ℃ .SHWG to proved 33.46 MW**,** the heat need in the economizer IP ,in the solar integarted combined power plant.

Table -3: Flue gases outlet temperature from HRSG unfired model (Case A) of Integrated Solar Combined Power Plant.

NO.	Type	Symbol	Calculation	Results
1	The outlet temperature of flue gases from the superheater	$T_{g,1}$	$Q_{sup} = \dot{m}_g C_{p,g}(T_{gi} - T_{g1})$	328.11 (°C)
2	The outlet temperature of flue gases from the economizer and HRSG	$T_{g,o}$	$Q_{econ} = \dot{m}_g C_{p,g}(T_{g1} - T_{go})$	148.36 (°C)
3	The efficiency of an Integrated solar power plant	η_{th}	$\eta_{th} = \frac{W_{net}}{\eta Q_{ff} + Q_{sol}}$	0.40

Table-4 : Heat required in the SSG model (Case A) of the Integrated Solar Combined Power Plant

No.	Type	Symbol	calculation	results
1	The heat source required	Q_{sol}	$= \mathring{m}_w h_{fg}$	179.57 MW
2	The heat gain required	$Q_{ga,o}$	$Q_{sol} = \varepsilon_{SHWG}\ Q_{ga,o}$	260.24 MW
3	The solar percentage	S	$= \frac{Q_{sol}}{Q_{sol}+Q_{ff}}$	0.3

Table - 5 : Flue gas outlet temperature from HRSG fired model (Case B) of Integrated Solar Combined Power Plant

NO.	Type	Symbol	Calculation	Results
1	Approach point	Δt_p	$\Delta t_p = T_{sat} - T_{w,i}$	0 (°C)
2	Pinch point HP	$\Delta t_{pp,2}$	$\Delta t_{pp,2} = T_{g2} - T_{sat,2}$	7 (°C)
3	Pinch point IP	$\Delta t_{pp,1}$	$\Delta t_{pp,1} = T_{g4} - T_{sat,1}$	9.7 (°C)
4	The outlet temperature of flue gases from the superheater HP	$T_{g,1}$	$Q_{sup,2} = \dot{m}_g C_{p,g}(T_{gi} - T_{g1})$	566.9 (°C)
5	The outlet temperature of flue gases from the evaporator HP	$T_{g,2}$	$Q_{evap,2} = \dot{m}_g C_{p,g}(T_{g1} - T_{g2})$	265.8 (°C)

6	The outlet temperature of flue gases from the superheater IP	$T_{g,3}$	$Q_{sup,1} = \dot{m}_g C_{p,g}(T_{g2} - T_{g3})$	256.58 (℃)
7	The outlet temperature of flue gases from the evaporator IP	$T_{g,4}$	$Q_{evap,1} = \dot{m}_g C_{p,g}(T_{g3} - T_{g4})$	174.7 (℃)
8	The outlet temperature of flue gases	$T_{g,o}$	$T_{g,o} = T_{g4} - R(T_{sat} - T_{w,i})$	68.97 (℃)
9	The efficiency of an Integrated solar power plant	(η_{th})	$\eta_{th} = \frac{W_{net}}{\eta\, Q_{ff} + Q_{sol}}$	0.5

Table – 6: Heat required in the SHWG model (Case B) of the Integrated Solar Combined Power Plant.

No.	Type	Symbol	calculation	results
1	The heat source required	Q_{sol}	$\mathring{m}_w \times C_{p,w,1}(T_{sat,2} - T_{sat,1})$	33.46 MW
2	The heat gain required	$Q_{ga,o}$	$Q_{sol} = \varepsilon_{SHWG}\ Q_{ga,o}$	48.50 MW
3	The solar percentage	S	$= \frac{Q_{sol}}{Q_{sol}+Q_{ff}}$	0.07

VI .Conclusions:

The efficiency of Integrated Solar Combined Power Plant can be increased from 40% for case A to 50% for case B, by changed type of Heat Recovery Steam Generator HRSG, so that the efficiency of integrated solar power plant with firring HRSG type is higher than the integrated solar power plant with unfired HRSG type, because of increase heat available in flue gases inlet HRSG, due to use burner duct located at inlet of HRSG before superheater. In general thermal environmental pollution with firing HRSG higher than unfired HRSG type, but in this case the opposite happened, due to used mltui pressure with firing HRSG, and single pressure with unfired HRSG.

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