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EXERGY ANALYSIS OF INTEGRATED SOLAR COMBINED CYCE POWER PLANT USING FOG SYSTEM.

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ABSTRACT
Nowadays the Integrated Solar Combined Cycle Power Plants (ISCCPPs) have an important role in efficient power generation especially at desert areas. Thermodynamic cycle development and integration are among the possible ways to enhance performance of power plants. In this study attempt will be made to investigate the effect caused by GT inlet Fogging to ISCCPP based on the average ambient condition. Recovery of HRSG blow down concerning cool down, as input to GT Inlet fogging will present as economic idea to enhance efficiency of overall cycle. Moreover, Exergy and performance of plant calculated to shows irreversibility of each part of Solar Combined Cycle including Compressor, GT, HRSG, Solar field and ST with different effectiveness of inlet fogging system. The Yazd 467 MW ISCCPP that located at desert area on Iran has been selected as large-scale applications study. The results show that the most exergy destruction in the ISCCPP occurs in the combustion chamber, HRSG, collectors, turbine, and solar field due to its high irreversibility.

INTRODUCTION
The global temperature has increased gradually due to global warming. The growing demand of energy of 1.6% per year, predicted by International Energy Agency (IEA), in the period 2006 to 2030 [1]. In other side gas turbine output is significantly affected by the ambient air temperature [2]. The increase in ambient air temperature also causes a significant increase in the gas turbine transfer heat rate and consequently operating cost rate.[3].According to researches renewable energy contributes to only 11% of the world primary energy and this is expected to increase to 60% by 2070[4] so most of existing power plants look for development and integration to renewable energy decelerated as the most readily available technical advances exploited. Furthermore, in large-scale power generation (>150 MW) it is generally cost effective to use Power Augmentation Technology (PATs) such as steam injection, humid air injection and gas turbine inlet air cooling like inlet evaporative, inlet chilling, high pressure fogging and Overspray.

NOMENCLATURE

A	*m2*	area
φ	*Degree*	angle of incidence
ε	*[-]*	Effectiveness of the inlet fogging system
K(φ)	*[-]*	incidence angle modifier
ω	*[-]*	Absolute humidity
$\dot{m}_0$	*[kg/s]*	Original design mass under ideal conditions
T	*[k]*	Temperature
τ	*[-]*	atmospheric transmittance for direct radiation
υ	*[m3/kg]*	Specified volume
κ_a	*[-]*	Specific heat ratio for air
r_p	*[-]*	Pressure ratio
Δp	*[kpa]*	Pressure drop
P	*[pa]*	Pressure
η_{comp}	*[-]*	Compressor isentropic efficiency
SF		Solar field
HDC		Hot day case
HPF		high pressure fogging
PAT		Power Augmentation Technology
DNI	*W/m2*	Direct Normal Irradiation
HTF		Heat Transfer Fluid
LHV	*[KJ/Kmol fuel]*	Low heating value of fuel
U		Heat Transfer Coefficient
w	*[KJ]*	Work
DBP	*[kpa]*	Outlet pressure at the turbine's exit
P_{GT}	*[KW]*	Output power of the gas turbine
η_{2GT}	*[-]*	Gas turbine second thermal efficiency
Subscripts		
o		optical, outlet
abs		absorber
bf		Before filter
wb		Wet bulb
inf		Inlet air of compressor by fog system
f		Fuel
a		Ambient

The combined cycle power plant (CCPP) is the most efficient option that is already achieving efficiencies well over 57%, with plant capacities in the range between 350 and 500MW [5].
The scope of this paper is to examine, effect of FOG system to ISCCPP and recovery of the HRSG blow down to FOG system as input regarding to reduce overall cost including water consumption, and cycle promotion. Integrated Solar Combined Cycle Power Plant (ISCCPP) have been widely studied as an alternative to the conventional arrangement of parabolic through collectors coupled to a Rankin power cycle a specific configuration of ISCC plant is proposed, and the coupling between the solar field and the combine cycle is studied. For that, the annual performance of the innovative proposed configuration defined. The main emphasis of this paper is to investigate the new configuration and effect of Fog system to ISCCPP and Exergy study of overall plant.

REVIEW OF GAS TURBINE POWER AUGMENTATION TECHNOLOGY (PAT)

The most important power augmentation options implemented and/or developed include steam injection, humid air injection and gas turbine inlet air cooling like inlet evaporative, inlet chilling, high pressure fogging and overspray. It is important to note that various inlet cooling techniques, available in the market today, have certain limitations such as modifications in the plant layout combined with increased investment and operating cost with continuous cooling, or thermal energy Storage approach and low evaporation efficiency with conventional media type evaporative cooling systems. Similarly, inlet fogging approach may not be advantageous at locations where shortage of a water source exists or if the ambient conditions are very humid [6].

EFFECT OF HIGH PRESSURE FOGGING (HPF) TO GT

Gas turbine HPF (Fig. 1) is a method of cooling the intake air where dematerialized water is converted into a fog by means of atomizing nozzles, usually operating at high pressure (80-200 bar) in order to obtain a fine droplet size. The cooling effect is provided by water evaporation; this
Technique allows close to 100% evaporation effectiveness in terms of attaining saturation conditions and wet bulb temperature at the GT inlet (transformation 1-4 in Fig. 2).With this strategy, the amount of injected water into the compressor inlet duct is strictly necessary for air saturation and water evaporation is completed before air enters into the compressor [7,8].

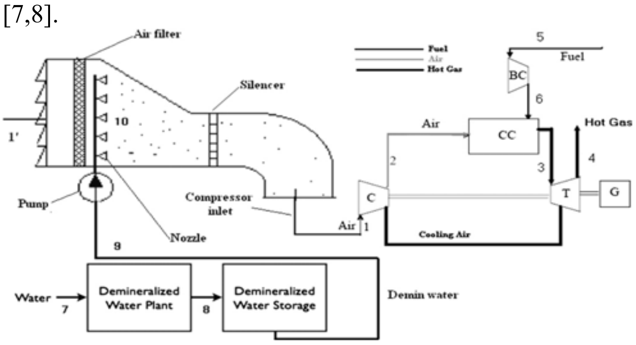

Fig.1. GT with FOG system: HPF

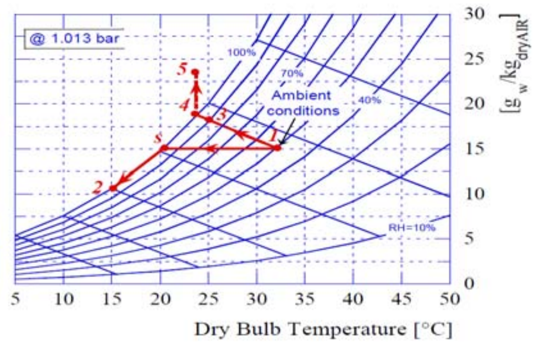

Fig.2 Humid air transformations for the inlet air cooling techniques.

EFFECT OF FOG ON ISCCPP

Integrated Solar Combined cycle power plant (ISCCPP) performance is also influenced by an increase in the ambient temperature because of decrease in the GT performance and efficiency of the cooling system (depending on the cooling system type) associated with a condensing steam turbine (ST).
One way to prevent the loss in performance of CCPPs, caused by high ambient temperatures, is to cool air at the inlet of gas turbine compressor. By inlet fogging heat recovery steam generator (HRSG) with supplementary firing and their combinations to augment power for combined cycle plants during peak demand periods were evaluated by Tawney et al. [9]. Their study revealed that under given economic conditions and operating dispositions, inlet fogging combined with a supplementary fired HRSG showed comparatively higher return on investment for combined cycle applications. Jones and Jacobs [10] presented a detailed review of available options for enhancing combined cycle performance. Their study also included an economic assessment of performance enhancement alternatives by considering a combined cycle plant consisting of two GE PG7241_FA_ gas turbines, two unfired three-pressure level HRSGs, and one GE D11 reheat condensing steam turbine with a wet cooling tower.

ISCCPP CONFIGURAION EQUIEPED WITH FOG AND RECOVERY OF BLOWDOWND

Fig. 3 shows a schematic diagram of the system under modification of cycle. For case study the YAZD ISCCPP selected to investigation. This power plant which is located in Yazd, Iran contains two 159 MW GT V94.2, a 160 MW ST E-typ. (GTs, ST manufactured in MAPNA GROUP), and a 17 MW solar Field which is under construction. In this system a combined cycle unit that some specification mentioned in table 1.

Table 1

GT V94.2 –TUGA	159	MW	Amb temp.	19	˚C
GT gas flow	428.4	kg/s	RH	32	%
HRSG HP pressure	84.8	Bar	Wind Speed	3	m/s
HRSG LP pressure	9.1	bar	Net Heat Rate of GT	15039	Kj/Kwh
HRSG HP temp.	506	˚C	TOT	548	˚C
HRSG LP temp.	231.6	˚C			

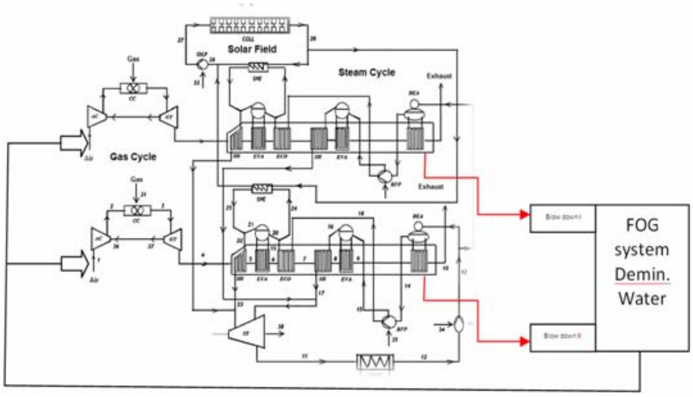

Fig. 3 .Schematic of ISCCPP equipped with Fog and innovative configuration for recovery blow down wastewater

SOLAR FIELD

The solar field considered in this site is comprised of 42 loops and for each loop, six collectors from type of LS-3 [11] which are single axis tracking and aligned on a north–south line, thus tracking the sun from east to west. Various design parameters of these Collectors are given in Table 2

Table 2. LS-3 collector type specification [11]

Aperture area per SCA (m2)	545	HCE emittance	0.17
Mirror segments	224	HCE transmittance	0.96
Aperture (m)	5.76	Mirror reflectivity	0.94
HCE diameter (m)	0.07	Length	99
Average focal distance (m)	0.94	Concentration ratio	82
HCE absorptivity	0.96	Peak collector efficiency (%)	68
Optical efficiency (%)	80	Annual thermal efficiency (%)	53

PARAMETER ANALYSIS OF ISCCPP WITH INLET FOGING OF GT$_S$

The effect of inlet fogging system on the thermodynamic properties is brought in Chiang and Wang [12]. The effectiveness of the inlet fogging system can be written as:

$$\varepsilon = \frac{T_{bF} - T_{inF}}{T_{bF} - (T_{wb})_{inF}} \tag{1}$$

Mass flow rate of water obey follow relation:

$$\dot{m}_w = (\omega_{inF} - \omega_{bF})[\frac{v_{ao}}{(v_a)_{inF}}][\frac{\dot{m}_o}{(1+\omega_o)}] \tag{2}$$

where ω_{inF} is the absolute humidity of inlet air in compressor with fog system, ω_{bF} is absolute humidity of air before filter, ω_0 is absolute humidity of original design under ideal conditions and $\dot{m}_0$ is original design mass under ideal conditions. Moreover, the ratio of specific volume is equal to ratio of dry-bulb and wet-bulb temperature before filtering Mass flow rate of compressor inlet with inlet fogging:

$$\dot{m}_{inF} = \dot{m}_o[\frac{v_{ao}}{(v_a)_{inF}}]\frac{(1+\omega_{inF})}{(1+\omega_o)} \tag{3}$$

COMPRESSOR

The compressor isentropic efficiency is $\eta_{compressor}$ and the isentropic outlet temperature leaving the compressor is determined by:

$$T_{2s} = T_1 (r_p)^{\frac{k_a - 1}{k_a}} \tag{4}$$

The rising isentropic temperature is:

$$T_{sr} = T_{2s} - T_1 \tag{5}$$

The rising actual temperature in the compressor is calculated from the definition of isentropic efficiency:

$$T_{ar} = \frac{T_{sr}}{\eta_{compressor}} \tag{6}$$

So, the actual outlet temperature leaves the compressor is:

$$T_{2a} = T_1 + T_{ar} \tag{7}$$

The actual work consumed by the compressor is given by:

$$W_{compressor} = \dot{m}_{inF} C_{pa} T_{ar} \tag{8}$$

COMBUSTOR

The specific heat of the flue gas is C_{pg} and The fuel mass flow rate is determined as:

$$\dot{m}_f = \frac{q_{in} / LHV}{\eta_{combustion}} \tag{9}$$

Also, the Air-fuel ratio can be obtained by:

$$f = \frac{\dot{m}_{inF}}{\dot{m}_f} \tag{10}$$

As a result, the heat exchange into the combustor can be computed from energy balance across the combustor:

$$q_{in} = \dot{m}_{inF} C_{pg} (T_3 - T_{2a}) \tag{11}$$

TURBINE

The work produced from the turbine is achieved as:

$$w_{turbine} = \dot{m}_{tot} C_{pg} T_{4a} \tag{12}$$

The output power of the gas turbine power plant is:

$$P_{GT=} P_t - P_c - (P_{MC})_{loss} - (P_G)_{loss} \tag{13}$$

The gas turbine thermal efficiency is:

$$\eta_{GT} = \frac{P_{GT}}{q_{in}} \tag{14}$$

HEAT RECOVERY STEAM GENERATOR (HRSG)

The efficiency of HRSG can calculate from equation:

$$\eta_{HRSG} = \frac{\text{ActualHeat Recovered}}{\text{GTexhaustEnergy} + (\text{LHV}_f)_{DB} + E_{Solar}} \qquad (15)$$

SOLAR FIELD ANALYSIS

To evaluate the performance of the solar field, it is necessary to estimate the solar radiation intensity from sunrise to sunset. The DNI, of course, depends on the local weather conditions at the site where the power plant is built. The solar field is made up of a numerous parabolic trough collectors. The useful energy gained by each collector can be given as a function of absorber temperature:

$$Q_c = A_c DNI \cos\varphi \eta_o K(\varphi) - A_{abs} U_{abs} (T_{abs} - T_a) \qquad (16)$$

The adopted methodology to estimate the direct solar irradiation intensity is the Hottel method. [13]

$$DNI = \tau \, \text{I} \cos\varphi \qquad (17)$$

The total useful energy gained by the heat transfer fluid in the solar field is:

$$Q_{SF} = N_C Q_C \qquad (18)$$

The inlet and outlet temperatures of HTF are set invariable. And the mass flow is:

$$\dot{m} = \frac{Q_{SF}}{[C_{pf}(T_{fo} - T_{fi})]} \qquad (19)$$

Finally overall efficiency of solar field calculated with :

$$\eta_{SF} = \frac{Q_{SF}}{[DNI.A_C.N_C]} \qquad (20)$$

$$\eta_{energy}\Big|_{collector-loop} = \frac{Q_{th.net}}{DNI_{incident}}\Bigg|_{collector-loop} \qquad (21)$$

Where η energy is the energy efficiency; $Q_{th,net}$ (kWh) is the net heat gain per collector loop; DNI incident (kWh) is the incident DNI normal to the collector aperture area.
Solar field performance under different irradiation values and outlet pressures shows in fig 4

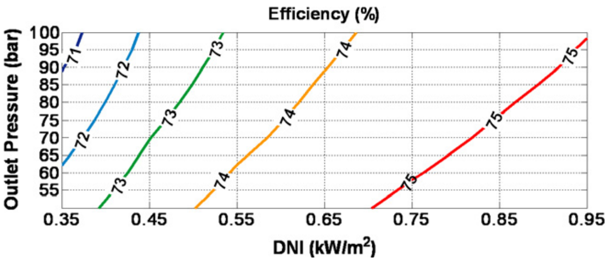

FIG.4 Solar efficiency per collector loop as a function of the DNI and the outlet solar field pressure

Fig.7 [15]

Comparison of first and second law analysis on each subsystem of collectors field.

subsystem	Irreversibility (MW)	Energy loss (%)	Exergy loss (%)	First law efficiency (%)	Second law efficiency (%)
Collector	64.22	20	58.8	80	41.1
Receiver	15.04	43.14	33.49	56.8	66.5
Collector-receiver	79.26	54.5	72.62	45.4	27.37

ISCCPP CYCLE

According to fig. 3 the overall efficiency of plant can obtain form this formula

$$(\eta_{ISCC})_{Gross} = \frac{P_{GT1} + P_{GT2} + P_{ST}}{\dot{Q}_{GT1} + \dot{Q}_{GT2} + \dot{Q}_{DB1} + \dot{Q}_{DB2} + \dot{Q}_{Solar}} \qquad (22)$$

$$(\eta_{ISCC})_{Net} = \frac{P_{GT1} + P_{GT2} + P_{ST} - P_{Comp1} - P_{Comp2}}{\dot{Q}_{GT1} + \dot{Q}_{GT2} + \dot{Q}_{DB1} + \dot{Q}_{DB2} + \dot{Q}_{Solar}} \qquad (23)$$

The HTF mass flow rate, the thermal efficiency and solar field output increase according to the increase in solar radiation from sunrise till sunset of each day, where the operation duration varies for each day. The amount of solar field output during the summer is greater than for the other seasons due to the higher solar radiation intensity and longer solar radiation duration. The period of peak solar field output generally occurs between 10a.m to 16p.m of each day. In summer, the solar thermal energy is about 17 MW at midday. At this time, the HTF mass flow is in the order of 13.1 Kg/s. As a result, the solar field collector efficiency reaches approximately 0.80

EXERGY ANALYSIS OF ISCCPP

Exergy analysis is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for analysis of ISCCPP and improvement of the plant. This tool used to efficient Energy-resource consumptions and study behaviour of cycle. Exergy study of GT cycle including FOG system performed before researches. The fluid that used (thermal oil-66) has temperature range 263-616(K) density 750Kg/m3 (average density and specific heat in the temperature range given.), specific heat rate 2100 J/kg.K and volumetric heat capacity is 1575 Kj/m3.K
In the operation strategy, the inlet and outlet temperatures of the heat transfer fluid remained constant and equal 212, 314˚C
The comparison of first and second low analysis on each subsystem of collector field shown in Fig.7
Respectively for a constant specific heat thermal fluid we have:

$$dQ = d(c_p \dot{m} T) = c_p \dot{m} \, dT \qquad (24)$$

$$Q = \int_{T1}^{T2} dQ = C_P \dot{m} (T_2 - T_1) \qquad (25)$$

The Exergy that transferred for solar heat carrier (LS-3) is given as bellows Eq. [14]

$$Ex_Q = Q\left[1 - \frac{T_a}{T_2 - T_1} \ln\left(\frac{T_2}{T_1}\right)\right] \qquad (26)$$

As a consequence, one has the exergetic efficiency of the collector as follows:

$$\eta_{II,collector} = \frac{Ex_Q}{Ex_{Solar}} = \frac{Ex_Q = Q\left[1 - \frac{T_a}{T_2 - T_1}\ln\left(\frac{T_2}{T_1}\right)\right]}{\frac{1}{T_2 - T_1}\int_{T_1}^{T_2}\frac{1}{\eta_{1,collector}\{T\}}dt\left(1 - \frac{4}{3}\frac{T_a}{T_S}\left(1 - 0.28\ln f\right)\right)} \qquad (27)$$

Where Ta is ambient temperature, T1 and T2 are temperature of fluid affected by collectors.

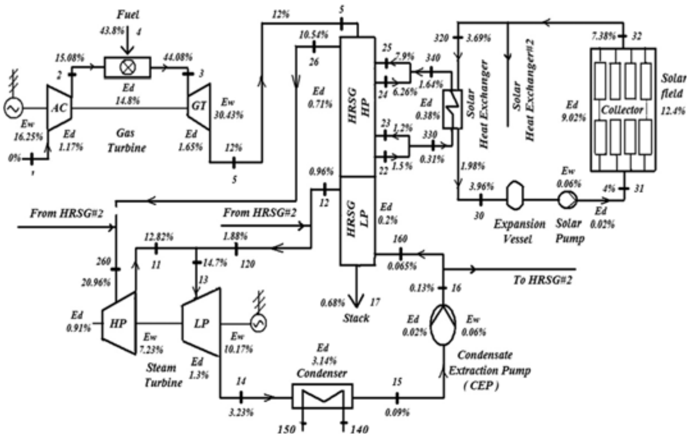

FIG.5. Exergy diagram of an ISCCS

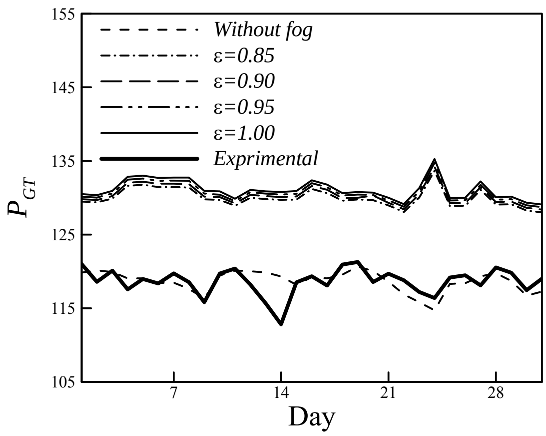

Figure 6 Effect of fogging on the GT net power output

CONCLUSION

In this paper, we have conducted thermal performance simulation for ISCCPP with inlet fogging system that supplied demonetized water from HRSG blow down .the result shows that the Power gain of Integrated Solar Combined Cycle Power augmentation by inlet fogging system under various ambient condition is about 0.40% to 0.65% in net output for every 1°C of inlet air-cooling regarding to Fog system. The gain in net power output due to overspray fogging is mainly associated with the performance enhancement in the gas turbine section of a ISCCPP Fig 6. The effect of fogging on steam turbine power output is small, compared to the GT power output boost, and especially no significant change seems to exist between ST power boost and the type of applied fogging strategy. The result show that the ISCCPP (Fig.3) power augmentation by inlet fogging is around 6 MW to 31MW .in other word increase about 1% to 5.1% power output of ISCCPP under study. Also first and second efficiencies of GT cycle will increase around 1.25 to 2.85 percent and 2 to 4 percent respectively.

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